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UNIVERSITÉ DE MONTRÉAL

# UNIFIED KERNEL/USER-SPACE EFFICIENT LINUX TRACING ARCHITECTURE

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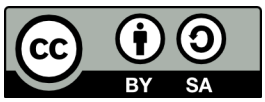

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# RÉSUMÉ

De nos jours, il n'est pas inhabituel de voir de grands centres de données regroupant des centaines de serveurs déployant de grosses applications, des systèmes d'exploitation hétérogènes et différentes technologie de virtualisation. Implanter du traçage dans ce genre d'environnement peut s'avérer utile pour la surveillance et le débogage de problèmes de production. Avec les dernière architecture de traçage développé, il peut être difficile d'atteindre un tel objectif dans un environnement multi-utilisateur et également traiter les questions de sécurité.

Dans cette recherche, nous proposons une nouvelle architecture de traçage unifiée combinant l'espace noyau et utilisateur visant à répondre aux contraintes de production en termes de sécurité et de performance. Avec le traceur en espace utilisateur, le nombre de sources de données augmentent, où non seulement le noyau peut être tracée mais plusieurs applications en même temps.

Cette nouvelle architecture présente un démon de session qui devient une nouvelle composante de traçage agissant comme un point de rendez-vous pour toutes les interactions avec les traceurs. Ce démon agit comme un registre de sessions de traçage pour les utilisateurs abstrayant les traceurs à des domaines. Nous proposer un ensemble de structure de données sans verrou et des algorithmes utilisés pour construire la base de registre rendant cette composante très performante.

Cela a permis la création du projet *lttng-tools*, basée sur les traceurs de LTTng 2.0, qui met en oeuvre l'architecture proposée. Nous avons développé plusieurs algorithmes pour gérer et fournir un système multi-session et multi-utilisateur tout en gardan une empreinte mémoire et CPU basse sur la machine cible. Avec l'abilité du traceur de l'espace utilisateur de s'enregistrer au démarrage au démon de session, de nouvelles fonctionnalités sont disponibles comme lister des applications tracable et de permettre de tracer des évènements disponibles seulement au démarrage de l'application.

Nous avons démontrer l'exactitude de notre modèle en utilisant le traçage noyau par ce nouveau composant pour analyser la performance de grosses applications de qui a été inspiré la conception des mécanismes internes de parallélisme.

Enfin, cette étude présente les travaux futurs et les améliorations possibles du modèle proposé et examine les défis à venir.

# ABSTRACT

Nowadays, it is not unusual to see large data centers regrouping hundreds of servers mixing large applications, heterogeneous kernels and different virtualization technology. Deploying tracing in these kinds of environments can prove to be useful for monitoring and debugging production problems. With today's tracing architecture, it can be difficult to achieve such goal in a multi-user environment while also dealing with security issues.

In this research, we propose a new unified tracing architecture combining kernel and user space aimed at addressing production constraints in terms of security and low-instrusiveness for large scale deployment. With user space tracers, data sources increase where not only the kernel can be traced but multiple applications at the same time.

This new architecture introduces a session daemon which becomes a new tracing component acting as a *rendez-vous* point for all interactions with the tracers. This daemon acts as a tracing registry providing tracing sessions to users, abstracting tracers to domains. We propose a set of lockless data structures and algorithms used to build the registry and making this component very efficient.

This brought to life the `lttng-tools` project, based on the LTTng 2.0 tracers, which implements the proposed architecture. We have developed several algorithms to handle and provide a multi-session and multi-user tracing environment with a low memory and CPU footprint on the target machine. With the user space tracer ability to register at startup to the session daemon, a new set of features are available, from listing traceable applications to enabling events before registration, allowing recording of very early events during the boostrap process of the program.

We have demonstrated the usability of our model by using kernel tracing through this new component to analyze the performance of large applications, which inspired us to design internal multithreaded mechanisms.

Finally, this study presents future work and possible improvements to the proposed model and discusses the next challenges.

# CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF APPENDICES

# LIST OF SIGNS AND ABBREVIATIONS

| | |
|---|---|
| API | Application Programming Interface |
| ASCII | American Standard Code for Information Interchange |
| BLOB | Binary Large Object |
| CLI | Command Line Interface |
| CPU | Central Processing Unit |
| GDB | GBU Debugger |
| FIFO | First In First Out |
| HTTP | Hypertext Transfer Protocol |
| I/O | Input/Output |
| IP | Internet Protocol |
| IPC | Inter Process Communication |
| IT | Information Technology |
| LDAP | Lightweight Directory Access Protocol |
| LTT | Linux Trace Toolkit |
| LTTng | Linux Trace Toolkit Next Generation |
| POSIX | Portable Operating System Interface for Unix |
| PID | Process Identifier |
| RCU | Read-Copy Update |
| SHM | Shared Memory |
| SMP | Symmetric Multiprocessing |
| SSL | Secure Socket Layer |
| TCP | Transport Control Protocol |
| UST | User Space Tracer |
| UID | Unique Identifier |
| UUID | Universal Unique Identifier |

# CHAPTER 1

# INTRODUCTION

Since the beginning of the LTTng project, and the release of its low-intrusiveness Linux tracer, tracing is used on a daily basis in very large data centers from small and medium companies like Revolution Linux to large corporation like Ericsson and Google. Over time, it has proven that it is not only useful for debugging complex performance problems. An increasing number of people are looking at tracing as a new tool for monitoring health of large computer clusters.

However, production deployment is still not mainstream. Key aspects are missing for it to be considered an essential production infrastructure component. Efficient tracers and data analysis tools are not enough.

## 1.1 Tracing overview

In order to understand the research problem, this section makes a brief overview of tracing by defining basic concepts used throughout this document.

On popular operating systems such as Linux, tracing is the action of recording *events* or "trace events" with a minimum of disturbance. In other words, it is an high throughput and efficient `printf` used to extract information from a running system, either from the kernel or from a simple user space application.

To achieve such goals, instrumentation is enabled on a trace source (Ex: kernel) called *tracepoints*. It can be added statically at the source code level or dynamically during runtime. Unlike traditionnal debug statements, tracepoints can be enabled or disabled at any point during the system lifetime. When a tracepoint is reached during execution, a *probe*, connected to it, is responsible for writing the data to buffers managed by the tracer. For each tracer, there is a consumer with a single task, writing the gathered information to a device (Ex: disk, network card).

A tracer is considered a *tracing source*, i.e. providing information for one contained system like the kernel or an application. With user space tracing, multiple sources are possible and can be merged with kernel data for extensive analysis of an application behaviour.

The amount of data generated by tracers can be pretty large hence analysis tools like

LTTV or TMF (Tracing Monitoring Framework) developed by Ericsson are used to display and understand collected data.

## 1.2 Problem

Today, many servers are running large number of applications with many different users. Thus, there is, at an unknown rate, always new programs spawning, chaging state (blocked, sleeping) and dying due to constant user interactions and potential heavy workload (Web servers). We are faced with new challenges both in terms of security and management of multiple tracing sources at once.

As mentionned, security is a very important issue here. Both user access control and data security have to be taken into account considering, for example, that critical applications like Web transactional software can be traced. With multiple programs running with different security credentials, it makes sense to consider managing user space tracing with a trusted central entity following an important security rule which is that no unprivileged user should be trusted.

The problem studied in this work is how can we achieve tracing in a production environment and still address resource usage and security constraints, using the LTTng tracer as research vehicle. We then propose a new architecture and demonstrate its effectiveness through the open source `lttng-tools` project which fulfills the needs for reliable tracing tools in both controlled and uncontrolled IT ecosystems.

## 1.3 Objectives

The methodology of this study focuses on the following four steps and resulted in a working implementation of our proposed model 3.1. The objective is to come up with a new architecture designed to combine kernel and user space tracing with a low overhead on the system. Improving usability is also highly desirable.

1. Study tracing impact and needs for large scale deployment.
   Identify key architectural aspects of having tracing in production systems often involving machines with heavy workloads.
2. Create new algorithms and design model to achieve our tracing goals.
3. Implement new tracing components to validate our model and algorithms.
4. Provide measurements for reference baseline results.

## 1.4 Contribution

The main contribution of this research is the design and creation of a tracing architecture suited and ready for production usage. This work includes the creation of efficient scheme and algorithm used to handle tracing for multiple applications. Those schemes extensively use RCU lockless data structures.

- Lockless dispatch mechanism to a thread pool.
- Efficient tracing application registration scheme.
- Tracing registry and lockless management.
- Kernel and user space tracing control unification.

The implementation of this work ended being the `lttng-tools` project providing a central point of control for tracing in the LTTng 2.0 toolchain.

## 1.5 Outline

Chapter 2 presents the state of the art of tracing systems and focuses on the infrastructure design. This section is a complete study of tracing related work, and relevant multithreaded multi-user daemon applications (in other areas than tracing but facing similar architectural requirements).

Then, Chapter 3 presents the article *Unified efficient Linux tracing architecture combining kernel and user space* submitted to the ACM Operating Systems Review. This article details the core of our research contributions. Section 3.3 is a subset of the state of the art Chapter and adds a note on performance. Section 3.5 presents the proposed unified efficient tracing architecture. Subsequently, section 3.6 shows the experimental results and performance baseline of the implemented solution.

Chapter 4 follows with some discussions on other work done and consideration on non-implemented parts of the model.

We will conclude in Chapter 5 by summarizing our work, explaining limitations to the solution and possible future work.

# CHAPTER 2

# STATE OF THE ART

This chapter presents different tracing related software tools and how they coped with multi-user tracing of multiple sources, from a performance and security point of view. This is highly relevant since it defines part of a tracing model for production environments.

Following this, we examine the work done on multithreaded Linux daemons handling large number of user requests. The actual benefit of this study is to explore architectures developed in other fields to solve similar problems. Thus, looking at existing APIs and mechanisms to deal with a large number of applications, interacting with a central service concurrently, is directly relevant.

## 2.1 Tracing infrastructure

The first subsection gives an overview of past and present software tracing systems and their architecture and design choices. This part is needed to identify some key elements missing for a good production tracing infrastructure and understand success and failures.

### 2.1.1 Tracing systems

In early 1994, a technique called *dynamic instrumentation* or Dyninst API was proposed to provide efficient, scalable and detailed data collection for large-scale parallel applications (Hollingsworth *et al.*, 1994). Being one of the first tracing systems, the infrastructure built for data extraction was limited. The operating systems at hand were not able to provide efficient services for data extraction. They had to build a data transport component to read the tracing data, using the `ptrace` function, that was based on a time slice to read data. A *time slice handler* was called at the end of each time slice, i.e when the program was scheduled out, and the data would be read by the data transport program built on top.

Based on this technology, the DPCL project was created to extend the Dyninst tools using a robust scalable design. It offered, at the time, an API for installing and removing instrumentation from serial or parallel programs at runtime (Pase, 1998). The original motivation for DPCL was to provide application performance analysis tools for customers where no tool suppliers could build this kind of framework.

This framework provided components to manage tracing, with what they called *special daemons* that work in a client-server application scheme. The end-user-tools were able to communicate with a service provider (daemon) and that daemon could install, activate, deactivate and remove instrumentation in an application. Both synchronous and asynchronous requests could be handled. This instrumentation was defined combining *probe expressions* and *probe modules*, which is a concept that we will meet later in the Systemtap project.

DPCL introduced the concept of a central daemon processing client requests through a library. The client tool, wanting to create a connection to a process for data acquisition, spawned a *super daemon*, if it did not exist, that checked for a *normal* daemon. The normal daemon would change its ownership to the process credentials. The connection was then transfered to that daemon and a channel was opened to the target process. Thus, for each user, there was a DPCL daemon created. The infrastructure design was made to provide a secure infrastructure and to be scalable on multiple nodes. This way, *user a* cannot interact with the daemon of *user b* and vice versa. It basically offloads all access control to the kernel.

This framework made possible new tools like DynaProf and graphical user interface for data analysis (DeRose *et al.*, 2001). DynaProf is a dynamic profiling tool that provides a command line interface, similar to gdb, used to interact with the DPCL API and to basically control tracing all over your system.

Kernel tracing brought a new dimension to infrastructure design, having the problem of extracting data out of the kernel memory space to make it available in user-space for analysis. The K42 project (Appavoo *et al.*, 2002) used shared buffers between kernel and user space memory, which had obvious security issues. A provided daemon waked up periodically and emptied out the buffers where all client trace control had to go through. This project was a research prototype aimed at improving tracing performance. Usability and security was simply sacrificed for the proof of concept. For example, a traced application could write to these shared buffers and read or corrupt the tracing data for another application, belonging to another user.

At this point, we can see that a central tracing control daemon is often used to handle the tracing back-end and for security issues. It works basically as a *rendez-vous* point for the user and tracer to manage their interactions, and to isolate components from each other.

In the next sections, recent open source tracers and how they built their tracing infrastructure will be examined. Even though most of these are kernel tracers, some projects also mix user space tracing, bringing up new issues.

### LTT and LTTng

If we look at the first Linux Trace Toolkit project (LTT)(Yaghmour et Dagenais, 2000), it was designed to help finding performance issues in fairly complex Linux systems, and provide users with a view of the system behaviour. A set of tools was offered to interact with the tracer, and a user space daemon for data extraction. No user space tracing was offered at that time. Therefore, we ended up with a very basic control, for only one user and one tracing source, the kernel.

Its successsor, LTTng (Desnoyers et Dagenais, 2006), was designed to offer kernel tracing with low latency, deterministic real-time impact, small impact on the operating system throughput and linear scalability with the number of cores (Desnoyers, 2009). It was a new and greatly improved system that made possible new tracing technology to be incorporated in the Linux kernel, such as immediate values and tracepoints(Desnoyers, 2009). Still, the goal was to address important performance needs. The same subset of tools as the LTT project were offered to the user space for tracing control and data extraction but, again, only privileged users can use it and a single tracing source is available.

One common aspect of those two tracers is that tracing data can be fetched through a character device, for LTT, and, for LTTng, a per stream file descriptor exposed through the debugfs filesystem. For LTTng, a central daemon polls on all stream file descriptors (which is a blocking state) and, when data is available, it is consumed by writing to trace files that can later be analysed. Tracer control is achieved through the debugfs filesystem by writing commands to the right file representing a tracer object (Ex: events, channel).

Note that security was never a prerequisite during development since the kernel is the only data source and privileged credentials are always needed. Multiple user sessions are not supported so only one privileged user could trace the kernel at once, which is not well suited for production. Furthermore, tracing control was not integrated between the LTTng kernel tracer and the LTTng user space tracer (UST), which reduced usability.

### DTrace

Then, Sun Microsystems™ released, in 2005, `DTrace`(Cantrill *et al.*, 2004) which offers the ability to dynamically instrument both user-level and kernel-level software. As part of a mass effort by Sun, a lot of tracepoints were added to the Solaris 10 kernel and user space applications. Projects like FreeBSD and NetBSD also ported dtrace to their platform, as later did Mac OS X. The goal was to help developers find serious performance problems. The intent was to deploy it across all Solaris servers and to use it in production.

If we look at the DTrace architecture, it uses multiple data providers, which are basically

probes used to gather tracing data and write it to memory buffers. The framework provides a user space library *(libdtrace)* which interacts with the tracer through *ioctl* system calls. Through those calls, the DTrace kernel framework returns specific crafted data for immediate analysis by the `dtrace` command line tool. Thus, every interaction with the DTrace tracer is made through the kernel, even user space tracing.

On a security aspect(Gregg et Mauro, 2011), groups were made available for different level of user privileges. You have to be in the `dtrace_proc` group to trace your own applications and in the `dtrace_kernel` group to trace the kernel. A third group, `dtrace_user`, permits only system call tracing and profiling of the user own processes.

This work was an important step forward in managing tracing in current operating systems in production environment. The choice of going through the kernel, even for user space tracing, is a performance trade-off between security and usability.

### SystemTap

In early 2005, Red Hat released `SystemTap` (Prasad *et al.*, 2005) which also offers dynamic instrumentation of the Linux kernel and user applications. In order to trace, the user needs to write scripts which are loaded in a *tapset library*. SystemTap then translates these in C code to create a kernel module. Once loaded, the module provides tracing data to user space for analysis.

Two system groups namely `stapdev` and `stapusr` are available to separate possible tracing actions. The *stapdev* group can do any action over Systemtap facilities, which makes it the administrative group for all tracing control (Don Domingo, 2010) and module creation.

The second group, *stapusr*, can only load already compiled modules located in specific protected directories which only contain certified modules.

The project also provides a *compile-server* which listens for secure TCP/IP connections using SSL and handles module compilation requests from any *certified* client. This acts as a SystemTap central module registry to authenticate and validate kernel modules before loading them.

This has a very limited security scheme for two reasons. First, privileged rights are still needed for specific task like running the compilation server and loading the modules, since the tool provided by Systemtap is set with the setuid bit. Secondly, for user space tracing, only users in SystemTap's group are able to trace their own application, which implies that a privileged user has to add individual users to at least the *stapusr* group at some point in time, creating important user management overhead.

It is worth noting that the compilation server acts mostly as a security barrier for kernel module control. However, like DTrace, the problem remains that it still relies on the kernel for

all tracing actions. Therefore, there is still a bottleneck on performance if we consider that a production system could have hundreds of instrumented applications tracing simultaneously. This back and forth in the kernel, for tracing control and data retrieval, cannot possibly scale well.

### Perf and Ftrace

In 2008 came the kernel function tracer `Ftrace` designed by Steven Rostedt and Ingo Molnar, and targeting kernel developer's needs. It offered new features, not in LTTng at the time, and a mainline Linux tracer more efficient than SystemTap (which as of today is still not in the mainline kernel).

`Perf` made by Ingo Molnar and Thomas Gleixner, which also came in 2008, brought performance counters access coupled with a tracer that uses the available kernel instrumentation.

Like the previous project, those tools are aimed at providing system data, with minimal impact on the operating system. Most of the time, the kernel is the target and all tracing facilities are inside it.

To use `Ftrace`, every interaction with it is done through the `debugfs` filesystem in `/debug/tracing` subdirectory. Commands are executed by changing values in files located in this directory. For instance, enabling the function tracer would be as follows:

```
# echo function >/debug/tracing/current_tracer
# echo 1 >/debug/tracing/tracing_enabled
[actions]
# echo 0 >/debug/tracing/tracing_enabled
```

Looking at the traced data is done by reading the `trace` file for human-readable output. Files `latency_trace` and `trace_pipe` are also available from which the trace can be read, organized respectively by system latencies and to be piped in a command. A `trace_cmd` command is available to make tracing easier and user friendly.

`Perf` is similar to `ftrace`, also using `debugfs` for trace output and command input. A `perf` command is available which helps on the usability side. Here is an example of how to start tracing kernel events:

```
# perf record -c 1 -a -e sched:sched_wakeup
```

Option "-c 1" says to sample every event and "-a" to enable system-wide tracing. This command records all `sched_wakeup` events in the system.

However, the design does not support production infrastructure with unprivileged users accessing the data. Moreover, aggregating tracing data from multiple sources is not possible. Every command has to be done as root and cannot be executed otherwise.

**UST**

One of the first user space alternative to DTrace and SystemTap came in January 2010 with the first official release of the user space tracer (UST) made by Pierre-Marc Fournier at École Polytechnique de Montréal(Fournier *et al.*, 2009). Largely based on the LTTng kernel tracer, the goal was to offer a framework for developers to add static tracepoints to their applications and be able to trace them exclusively in user space (not using the kernel or having privileged rights like in the previous projects).

This project was the starting baseline of this study. The tools provided were not addressing production needs and security issues, thus making this tracer only used by developers. With an *in-process* library, this tracer brought new concepts to tracing and thus new challenges to make an integration in a *real world* environment. Among these challenges, is the multi-user aspect, handling tracing session on a per-user basis with multiple tracing sources.

One major factor of scalability is the one daemon per process design. With large number of applications being traced on a system, this scheme can consume a lot of resources (memory and CPU), thus degrading the server performance. However, the advantages of this tracer is that everything is done in user land, thus eliminating the need for a kernel component, bringing higher performance versus Dtrace and SystemTap. UST uses RCU data structures for a completely lockless tracer.

## 2.2 Multi-user architecture

We have highlighted in the last section that user space tracing brought issues to the production environment concept. In order to propose a new tracing component, the next sections explore multi-user support in areas other than tracing, and how widely used applications are dealing with it.

Through this research, we propose a new approach to tracing by combining kernel and user space tracing through one central component. As mentioned before, with user space tracing, systems can now have an large number of tracing sources in a multi-user environment. Knowing that, challenges arise on how can we manage a potentially large number of requests from users and applications to our central component by keeping it fast and efficient.

The following studied applications are routinely deployed across all types of servers and workloads and can manage numerous client requests to be served efficiently. They could

serve as an inspiration for a scalable tracing infrastructure and help us choose a design synchronization model.

### 2.2.1 Popular applications

#### Pulseaudio

Pulseaudio is a cross-platform networked sound server, commonly used on the Linux-based and FreeBSD operating systems (Wikipedia, 2011). It is the most widespread program in all Unix operating systems to manage sound I/O. Audio streams management, transport and composition has been a difficult problem with a large number of proposals through the years which failed to offer the desired scalability, performance and architectural soundness.

The pulseaudio daemon acts like a central *rendez-vous* point for all sound sources. It then reroute sound streams to the corresponding hardware or even over a network stack. Through a library layer, the pulseaudio server can be controlled from multiple applications and also acts as a sound system registry.

They extensively uses the POSIX thread library `(pthread)` for synchronization using mutexes and conditions. They also use shared memory for sound buffer sharing and semaphores for sound stream synchronization. This particular design is very interesting from a multi-source point of view, where one main server handles multiple commands, taken from a user space library API, and reroutes requests and replies through the server. Depending on the sound sources, the right hardware is chosen.

The routing commands concept was used in our work to develop a new tracing component sending client requests to tracers (tracing sources). We also created a similar API to control the central daemon handling tracing sources (here sound streams). The whole idea of being a *rendez-vous* point for sound sources is one of the core foundation behind our work.

#### Memcached

Memcached is an interesting software to look at in terms of distributed client and concurrent data access. Memcached is a high-performance, distributed caching system used to speed up applications by using unused memory across remote nodes (Fitzpatrick, 2004)(Petrovic, 2008). It uses a distributed hash table shared between nodes so that every change could be seen by every node. Keys in the global hash table represent memory segments that an application could request using the user-space API.

The basic tasks of memcached are:

– Manage memory allocation (malloc/free)

– Keep track of BLOB stored in memory

– Serve client for memory requests

The interesting aspect here to consider for this study is the storage technique used and effiency at getting coherent data between nodes. Using hash tables makes searches in $O(1)$ for every existing or non existing memory object lookup. Although our approach in this work is different, being not distributed, the concept of tracking memory and using hash tables is used for our purposes.

In terms of code and threading model, having thread workers handling client requests, since using TCP/IP sockets can be costly, is a nice model to consider.

**Apache 2.2 Web Server**

The Apache project came to life in 1995 (Fielding et Kaiser, 1997) and brought to the open source world one of the most powerful and widespread Web server. This software is currently used to handle most of the busy Web sites like Wikipedia.

Apache uses a thread pool scheme. It allocates resources for a fixed number of threads at startup, and dispatches requests among them. A process pool (workers) is created by the MPM module (*multi-processing module*) (Kew, 2007) to handle client requests. By looking at the dispatch mechanism, (i.e. how the main listener thread hands over a user request to a process in the pool), helped us design the main part of the lttng-tools project.

Basically, each worker waits on a global queue using the queue's global lock (pthread mutex (Rochkind, 2004)) and reads from the socket when it is able to acquire the lock. Once the element is read (here a HTTP request), it is processed by the worker thread. After finishing the request, the worker thread requeues itself by trying to reacquire the lock. The contention is basically handled by the kernel and starvation is avoided since this queue basically acts as a FIFO mechanism.

Section 3.6 looks at the time taken by the process to settle the contention between all worker threads and compares it to the proposed lttng-tools dispatch mechanism.

This overview of these three multi-user infrastructure applications, extensively used on high end production servers, gives us a good idea on how we can achieve our goals efficiently.

# CHAPTER 3

# UNIFIED KERNEL/USER-SPACE EFFICIENT LINUX TRACING ARCHITECTURE

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## 3.1 Abstract

As tracing becomes increasingly efficient, new applications are envisioned such as monitoring servers farms. When dealing with multiple tracing sources, from user to kernel space, a production grade architecture is needed to handle multi-user environments and security concerns. This work aims at creating a unified tracing architecture, combining tracers functionalities under one umbrella. The objective is to provide good performance and low resource footprint. This model motivated the `lttng-tools` project, based on the LTTng 2.0 tracers, which implements the proposed architecture.

## 3.2 Introduction

Tracing is used on a daily basis in large data centres from small companies to large corporation like Ericsson and Google. It has proven that it is not only useful for debugging complex performance problems (Bligh *et al.*, 2007) but people are looking at tracing as a new tool for monitoring the health of large computer clusters.

Bringing tracing into production systems involves multi-user environments. For instance, software developers using shared servers with different credential levels imply using a session mechanism in order to isolate these from each other. Furthermore, with user space tracing comes the aspect of multiple tracing sources, where a large number of tracers (e.g. traced applications) can be running at the same time and controlled by different users. Security is an important factor addressed with sessions at two levels: tracer access control, and reliable tracing control.

This paper presents a new unified infrastructure to trace multiple sources (kernel and applications). This infrastructure addresses multi-user and security constraints. Moreover, it keeps the low-intrusiveness and efficiency properties that modern tracers offer. By unifying tracer control, we proposed new tracing components which act as a *rendez-vous* point, handling data consumption and interactions between users and tracers.

To achieve this, we propose a new tracing architecture, suited for production environment, unifying kernel and user space tracing. The results of our study, based on the LTTng 2.0 tracer [1], resulted in the `lttng-tools` project.

In the next section, we present the existing work on tracing infrastructure from the design point of view. We also outline known multi-user multithreaded applications like Apache (Fielding et Kaiser, 1997) which address similar performance and efficiency concerns in a multi-user context. The following section 3.4 explains the design requirements for our architecture.

In section 3.5, we present our solution based on the aforementioned design requirements. This model was implemented in the `lttng-tools` project and now provides a new set of features. In section 3.6 experimental results are presented and demonstrate the performance and correctness of the proposed architecture and synchronization algorithms. We then conclude this research, briefly discussing areas for improvement.

1. `http://lttng.org`

## 3.3 State of the Art

This paper proposes a new tracing component not found in existing tracing solutions, as detailed in this section. For this reason, efficient multi-user infrastructure applications in areas other than tracing were also examined, to study how they handle multiple requests from clients and scale on multi-processor systems.

### 3.3.1 Tracing infrastructure

The first section gives an overview of current software tracing systems and the design choices they made.

Sun Microsystems™ released, in 2005, `DTrace` (Cantrill *et al.*, 2004) which offers the ability to dynamically instrument both user-level and kernel-level software. As part of a mass effort by Sun, numerous tracepoints were added to the Solaris 10 kernel and user space applications. Projects like FreeBSD and NetBSD also ported dtrace to their platform, as later did Mac OS X. The goal was to help developers find serious performance problems. The intent was to deploy it across all Solaris servers, to be used in production.

If we look at the DTrace architecture, it uses multiple data providers, which are probes used to gather tracing data and write it to memory buffers. The framework provides a user space library *(libdtrace)* which interacts with the tracer through *ioctl* system calls. Through those calls, the DTrace kernel framework returns specific crafted data for immediate analysis by the `dtrace` command line tool. Every interaction with the DTrace tracer is through the kernel, even for user space tracing. This creates an important bottleneck since the kernel handles every tracing source, slowing concurrent user space tracing.

On a security aspect (Gregg et Mauro, 2011), groups are available for different levels of user privileges. You have to be in the `dtrace_proc` group to trace your own applications and in the `dtrace_kernel` group to trace the kernel. A third group, `dtrace_user`, permits only syscall tracing and profiling of the user's own processes. This concept of tracing roles separation is good for dealing with credentials separation and not force users to have privileged rights (root).

In early 2005, Red Hat released `SystemTap` (Prasad *et al.*, 2005) which also offers dynamic instrumentation of the Linux kernel and user applications. In order to trace, the user needs to write scripts which are loaded in a *tapset library*. SystemTap then translates these in C code to create a kernel module. Once loaded, the module provides tracing data to user space for analysis.

Two system groups, namely `stapdev` and `stapusr`, are available to separate possible tracing actions. The *stapdev* group can do any action over Systemtap facilities, making it

the administrative group for all tracing control (Don Domingo, 2010) and module creation.

The second group, *stapusr*, can only load already compiled modules, located in specific protected directories which only contain certified modules.

The project also provides a *compilation server*, listening for secure TCP/IP connections using SSL and handling module compilation requests from any *certified* client. This acts as a SystemTap module central registry to authenticate and validate kernel modules before loading them.

This constitutes a very limited security scheme for two reasons. First, privileged rights are still needed for specific tasks like running the compilation server and loading the modules, since the tool provided by Systemtap is set with the setuid bit. Secondly, for user space tracing, only users in SystemTap's group are able to trace their own application, which implies that a privileged user has to add individual users to at least the *stapusr* group at some point in time, creating important user management overhead.

It is worth noting that the compilation server acts mostly as a security barrier for kernel module control. However, like DTrace, the problem remains that it still relies on the kernel for all tracing actions. Thus, there is still a bottleneck on performance if we consider that a production system could have hundreds of instrumented applications tracing simultaneously. Transitioning back and forth in the kernel for tracing control and data retrieval cannot possibly scale well.

Linux tracing is designed to be extremely efficient. Yet, until now, no existing solution provides good performance and security to handle tracing in a multi-user environment with multiple tracing sources.

### 3.3.2 Multi-user multithreaded application

Throughout this research, a main focus is to handle not only many users but also many tracing sources. The `memcached` and `Apache` project are two widespread applications that efficiently address these security and multi-user requirements.

This work proposes a new approach to tracing by combining kernel and user space tracing through one central component. As mentioned before, with user space tracing, a system can now have a large number of tracing sources in a multi-user environment. Knowing that, challenges arise on how can we manage a potentially large number of requests from users and applications to our central component by keeping it fast and efficient. Studying the following applications helped design our new architecture and algorithms for synchronization in a multithreaded environment.

### Memcached

Memcached is a very interesting system to look at in terms of distributed client and concurrent data access. It is a high-performance, distributed caching system, used to speed up applications by using unused memory across remote nodes (Fitzpatrick, 2004) (Petrovic, 2008). It uses a distributed hash table shared between nodes so every change could be seen by every node. Keys in the global hash table represent memory segments that an application could request using the user space API.

The basic tasks of memcached are:

– Manage memory allocation (malloc/free)
– Keep track of BLOB stored in memory
– Serve clients for memory requests

Interesting aspects to considered for this study are the storage technique used and efficiency at getting coherent data between nodes. Using hash tables enables searches in $O(1)$ for every existing or non existing memory object lookup.

Moreover, the client request handling threading model is based on `libevent` [2] which passes every new connection to a thread pool on a round-robin basis. However, to access the main hash table, a global lock is still needed, creating an important contention between requests.

### Apache 2.2 Web Server

The Apache project started in 1995 (Fielding et Kaiser, 1997) and brought to the open source world one of the most powerful and widespread Web server. It is used to handle several of the busiest Web sites like Wikipedia.

Apache uses a thread pool scheme. It allocates resources for a fixed number of threads at startup, and dispatches requests among them. A process pool (workers) is created by the MPM module (*multi-processing module*) (Kew, 2007) to handle client requests. Looking at the dispatching mechanism, i.e. how the main listener thread hands over a user request to a process in the pool, helped us design the main part of the lttng-tools project.

Each worker waits on a global queue using the queue's global lock (pthread mutex (Rochkind, 2004)) and reads from the socket when it is able to acquire the lock. Once the element is read (here a HTTP request), it is processed by the worker thread. After finishing the request, the worker thread requeues itself by trying to reacquire the lock. The contention is handled by the kernel and starvation is avoided since this queue essentially acts as a FIFO mechanism.

2. `http://libevent.org`

Section 3.6 looks at the time taken by the process to settle the contention between all worker threads, and compares it to the lttng-tools dispatching mechanism.

This overview of these multi-user infrastructure applications, extensively used on high end production servers, gives us a good idea on how we can achieve our goals efficiently.

### 3.3.3 Synchronization

Multithreaded applications come with important synchronization challenges. The key goal of our proposed architecture is to optimise the performance. A lockless scheme was devised using RCU technology (McKenney et Walpole, 2007) – a synchronization mechanism allowing reads to occur concurrently with updates. RCU enables concurrent access to data structures without locks for one updater and multiple readers. It differs from locking primitives that ensure mutual exclusion between threads, or reader-writer locks which allow concurrent reads but not during updates.

The basic idea is that updates are atomic, even for complex structures. A pointer to the complex structure is atomically replaced by another pointer to a fresh updated copy of the structure. Thus, while updating is protected by locks, reads can happen concurrently with updates and other reads. The tricky part in RCU algorithms is to determine when the previous version of the updated structure can be released, all concurrent reads accessing that version being terminated.

The user space RCU library (Desnoyers *et al.*, 2010) provides a wide variety of lockless data structures, from linked lists to red-black trees. They were used extensively for the synchronization model of our proposed tracing rendez-vous point.

## 3.4 Design Requirements

This research is in part intended to meet the requirements set by industry partners such as Ericsson and Revolution Linux who helped define the missing parts of today's tracing architecture. Four requirements were identified and are an important focus of this work.

1. Multi-user
2. Security
3. Performance
4. Reliability

Deployed servers support many users with different security rights and are often managed through a central directory (Ex: LDAP). For thin clients deployed by Revolution Linux [3], tracing cannot be deployed unless the multi-user constraint is addressed. Since we are dealing with multiple tracing sources, it becomes important that users do not interfere with each other. Hence a separation is needed in terms of data coherency and security.

The next key point to consider is security. Again, multiple users means different access levels, where everyone is not a privileged user. Tracing data from critical applications, for example banking software and sensitive databases, should not be accessible by unprivileged users for obvious reasons.

Furthermore, there is the question of trace data protection and integrity to consider. Fortunately, the tracer itself can guarantee the correctness of data written to buffers. However, unifying tracers implies aggregating tracing sources, so care is needed for managing those traces beyond the tracer lifetime.

Production servers should not suffer performance issues from tracing and it should scale throughout hardware and software upgrades (e.g. adding more cores).

Tracers usually outsource the extraction of recorded data from buffers to disk using a separate user space process. Indeed, LTT (Yaghmour et Dagenais, 2000), LTTng (Desnoyers et Dagenais, 2006), SystemTap (Prasad *et al.*, 2005) and DTrace (Cantrill *et al.*, 2004) all use kernel IPC (Love, 2010) mechanisms to notify a user space daemon to consume buffers. On large server farms, the scalability of the data retrieval and analysis infrastructure is a concern.

Different types of efficient data transport, subject to security constraints (integrity and protection), were examined during the architectural design. For instance, the types of transport investigated are network streaming (using either UDP or TCP), local device writing, secure communication layer like SSH protocol (Ylonen *et al.*, 2006) or memory caching (flight recorder).

Finally, a separation between the control and data path, for the telecommunication industry, is very important to ensure reliability of their software and hardware. One failing should not cause the other one to stop.

## 3.5 Unified tracing architecture

One of the main problems faced throughout this research, encountered during the design phase of `lttng-tools`, is how to integrate all tracing components and create a *rendez-vous* point for all tracing activities, while addressing the previous considerations.

3. `http://revolutionlinux.com`

With a set of design goals and use cases to address, this section explains in detail the work done to design an efficient tracing infrastructure. This resulted in the `lttng-tools` project, based on the LTTng tracer family (Desnoyers et Dagenais, 2006) (Desnoyers, 2012), an important benefit of this research to the tracing and open source communities.

The `lttng-tools` project regroups three components which now allow large scale deployment of applications instrumented with the LTTng user space tracer alongside with the kernel tracer. Figure 3.1 shows the global architecture model and the three components being the *lttng CLI*, *consumer daemons* and *session daemon*.

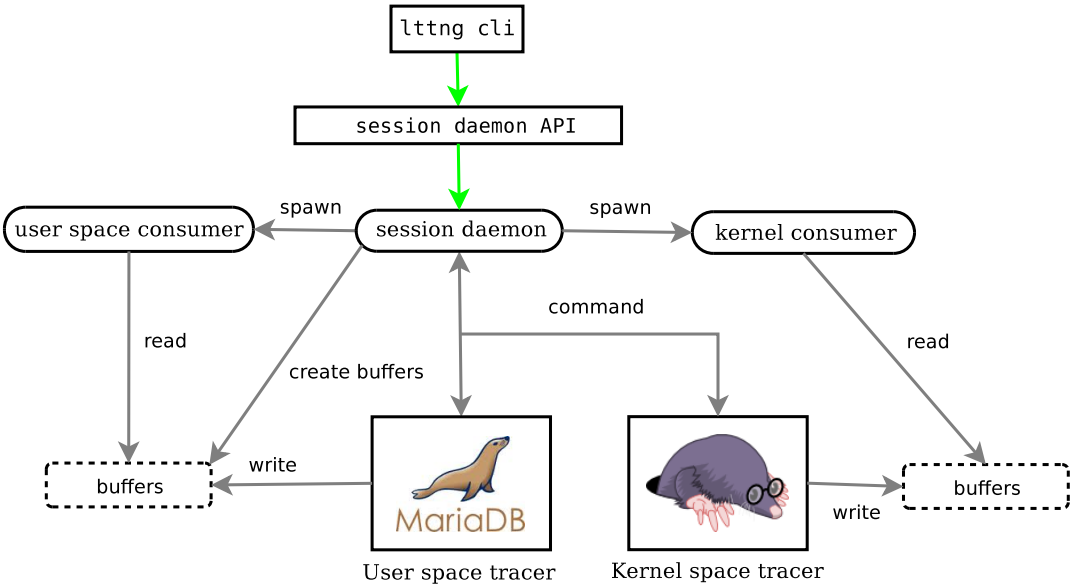



Figure 3.1 Architecture

The `lttng` command line interface is a small program used to interact with the session daemon. Possible interaction are creating sessions, enabling events, starting tracing and so on (Goulet, 2012). For more information, look at appendix D.

The session daemon is the new main component proposed in this work and is the central point handling tracers and users. Tracing sessions are used to isolate users from each other and create coherent tracing data between all tracing sources (Ex: MariaDB vs Kernel). This daemon routes user commands to the tracers and keeps an internal state of the requested actions. The daemon makes sure that this internal state is in complete synchronization with the tracers, and therefore no direct communication with the tracers is allowed other than via the session daemon.

This daemon is self-contained between users. Each user can run its own session daemon but only one is allowed per user. No communication happens between daemons. Section 3.5.2 explains this separation.

Consumer daemons extract data from buffers containing recorded data and write it to disk for later analysis. There are two separate consumer daemons, one handling user space and the second one the kernel. A single consumer daemon handles all the user space (and similarly for kernel space) tracing sessions for a given session daemon. It is the session daemon that initiates the execution of the user space and kernel consumer daemons and feeds them with tracing commands. The session daemon implements our proposed architecture.

For illustration purposes, here is a small example on how you start tracing the kernel using this new architecture.

```
# lttng create mysession
# lttng enable-event sched_switch --kernel
# lttng start
...
# lttng stop
```

First, a session is created using the `lttng` command line interface which send command to the session daemon. We then enable the event `sched_switch` for the kernel domain (–kernel). So, the daemon receives the command, maintain an internal state for the session and finally enables the event on the tracer. Following this, the start action basically spawn the kernel consumer and start tracing for every session. Upon the stop command, the consumer stays alive but the tracer stops recording data.

The next section describes important tracing concepts for the global understanding of the model. The following section presents the session daemon internal algorithms, key to its efficiency.

### 3.5.1 Tracing concepts

One of the goals of the lttng-tools project is to bring LTTng's tracers under one umbrella and creating an abstraction layer between the user and the tracers, hence the importance of the *rendez-vous* point concept.

#### Domains

First, we introduce the notion of *tracing domains* which is essentially, a type of tracer or tracer/feature tuple. We currently implement two domains in lttng-tools:

– `UST`

  Global user space domain. Channels and events registered in that domain are enabled on all current and future registered user space applications.

– KERNEL

Three more domains are not yet implemented but are good examples of the tracer/feature concept. They are UST_PID for specific PID tracing, UST_EXEC_NAME based on application name and UST_PID_FOLLOW_CHILDREN which is the same as tracing a PID but follows spawned children.

### Session

One of the key new features is the concept of *tracing session*. It is an isolated container used to separate tracing sources and users from each other. It takes advantage of the session feature offered by the tracer.

Each tracing session has a human readable name (Ex.: myapps) and a directory path where all trace data is written. It also contains the user UID/GID, in order to handle permissions on the trace data and also determine who can interact with it. We use credentials passing through UNIX socket (Rochkind, 2004) (Linux, 2008) for that purpose.

More importantly, it has pointers to each possible tracer session (kernel and user space). Each of them contains the list of domains which contain a list of channels. Appendix A shows the code snippet for the tracing session data structure.

### Event

In earlier LTTng tracers (version 0.x) (Desnoyers et Dagenais, 2006), the term tracepoint was used and represented a probe in the code recording information. Here, to abstract different domains, the term *event* is used which relates to a TRACE_EVENT statement in your application code or in the Linux kernel instrumentation.

Using the command line tool lttng D, you can enable and disable events for a specific tracing session on a per domain basis. An event is always bound to a channel and associated tracing context (Desnoyers, 2012).

### Channel

Channels existed in the earlier LTTng tracers but were hardcoded and specified by the tracer. In the new LTTng 2.0 version, channels are now definable by the user and completely customizable (size of buffers, number of subbuffer, read timer, etc.).

A channel contains a list of user specified events (e.g. system calls and scheduling switches) and context information (e.g. process id and priority). Channels are created on a per domain basis, thus each domain contains a list of channels that the user creates.

Each event type in a session can belong to a single channel. For example, if event A is enabled in channel 1, it cannot be enabled in channel 2. However, event A can be enabled in channel 2 (or channel 1 but not both) of another session.

### 3.5.2 Session daemon

The session daemon handles all interactions between the users, consumers and tracers. Here is the list of the daemon's roles. Each role is explained in depth to illustrate how are satisfied the requirements exposed in section 3.3.

- *Rendez-vous* point:
  Handles user, consumer and tracer interactions, being the synchronization component across the tracing toolchain.
- Act as a tracing registry:
  1. User space tracer registration (application register)
  2. Tracing sessions management (user command)

Unlike the DPCL(Pase, 1998) project using a *super daemon*, our session daemons coexist and act independently, never exchanging data, managing their instrumented applications with the same credentials and handling their own consumers.

It is possible for multiple users to run a session daemon at the same time on the same machine. Figure 3.2 shows the interaction between all the components in a multi-user environment. It should be noted that the two session daemons of the figure never communicate. Such separation is crucial for usability. It allows any user to compile its own session daemon, run it and be able to trace his or her applications independently. Having two session daemons communicating would be useless since the information of another user is irrelevant.

Section 3.5.2 explains the efficient mechanism behind applications and tracing sessions management.

For kernel tracing, the session daemon must run with privileged credentials (UID = 0). For obvious security reasons, only allowed users can gather kernel traces. A *tracing* group is defined, similar to SystemTap groups (Prasad *et al.*, 2005), where everyone in that group can communicate with the session daemon running as root. This is achieved by using Unix sockets (Rochkind, 2004) and having read and write permissions for the tracing group.

In summary, the session daemon grants access to tracing resources by running under various credentials and allowing interactions only from users who possess enough rights to do so. Unprivileged users cannot access other user's traces and only allowed users can control the kernel tracer. Moreover, the *rendez-vous* point concept allows it to provide a

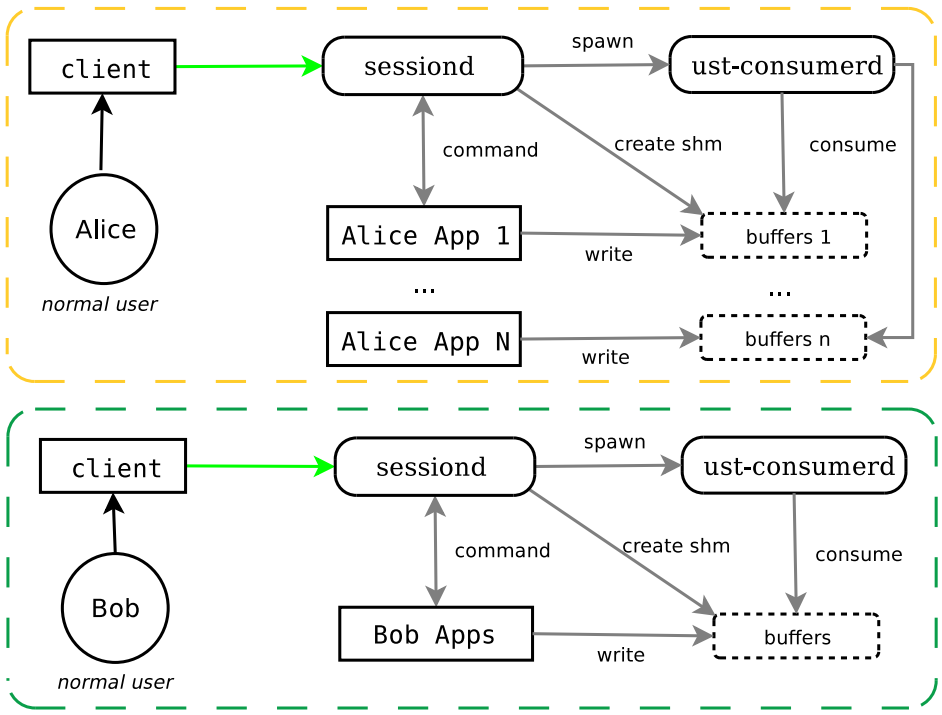



Figure 3.2 Multi-user scenario

new set of features that tracers themselves cannot provide such as application registration, and synchronization of every tracer available on the system.

The next two sections explains the user and kernel space tracer interactions with the session daemon, looking in depth at application registration and kernel features. Following this, the tracing registry, the core of the session daemon, is described.

### Kernel tracer

While the kernel tracer is the most complex entity in terms of code and algorithms, it is the simplest to handle. For the session daemon, this tracer is a single tracing source. You cannot have two kernels running concurrently, as opposed to user space tracers where multiple instrumented applications provide multiple tracing sources.

Managing the kernel tracer requires a different approach from user space tracing. The traced data is entirely controlled by the kernel. For security reasons, we can assume that they are not directly accessible by user space, at least not writable. As we saw in previous projects (Desnoyers et Dagenais, 2006) (Yaghmour et Dagenais, 2000) (Prasad *et al.*, 2005), the kernel exposes a transport pipeline (Ex: character device or anonymous file descriptor) and a user space daemon simply extracts data through this mechanism.

Mostly for security purposes, and buffering differences between tracers, the lttng-tools

project implemented a separate consumer for the kernel tracer. It is spawned and updated by the session daemon. At startup, the session daemon loads every LTTng kernel module and opens file `/proc/lttng` for upcoming interactions. As mention earlier, only a privileged session daemon can communicate with the kernel tracer, and only users in the tracing group can interact with it.

One specific feature of the kernel tracer is CPU hotplug. It is explained in section 3.5.2. The kernel notifications are handled by a thread that polls the kernel file descriptor notifies the consumer of the newly created per-cpu channel to consume.

#### User-space tracer

The user space tracer brings the possibility of multiple concurrent tracing sources. With the LTTng 2.0 UST tracer, instrumented applications register with the session daemon at the beginning of their execution.

Since the tracer functionality relies on a running session daemon, the registration mechanism is crucial and, thus, has to be very efficient. Two challenging situations occur, where the session daemon is either running or not running. The most important premise is that the application runtime behaviour should not be altered by the user space tracer waiting for the session daemon. Thus, the user space tracer needs to follow this algorithm in a separate thread, since condition at line 1 might not be satisfied at first:

**Require:** New process (thread)
1: **if** *connect succeed* **then**
2: register
3: receive possible command(s)
4: begin normal program execution
5: **else**
6: begin normal program execution
7: wait for notification (passive blocking)
8: **end if**

Line 1 tests the condition by connecting to the session daemon application socket. On success, the application sends basic information used by the application registry 3.5.2 on line 3. Then, it waits for commands (Ex: create session, enabling events, etc.) and finally begins the normal execution of the program (C `main()`).

On connection failure, we immediately begin the program execution since we cannot wait for an unknown period of time. Finally, on line 7, we wait for notification, which is the more

complex part.

Figure 3.3 shows the three possible scenarios for the session daemon notification process. Three applications begin waiting respectively before, during and after the notify (wake) of the session daemon which indicates that it is ready to receive registration.

*App1* and *app3* are clearly able to register since the state of the wake is not racing with the wait process and the registration. However, app2 is a more problematic case which requires careful synchronization in order to avoid starvation on the tracer side and the possible wait/wake race shown in figure 3.4. This model is based on the fact that there are $n > 0$ wait processes and 1 waker.

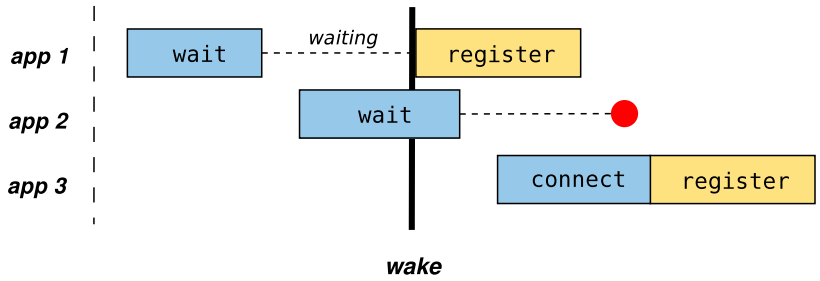



Figure 3.3 UST registration synchronization

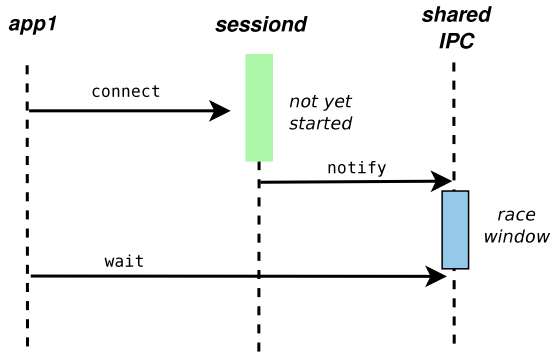



Figure 3.4 UST registration wait/wake race

This issue shows that a *shared IPC* is needed as a way to synchronize applications and a session daemon. A persistent memory location with the session daemon state (flag) is needed to ensure coherent state over time for all user space tracers. Commonly, this is called a semaphore (Abraham Silberschatz et Gagne, 2008) and we use it to synchronize processes.

We elected to use a shared memory area (SHM) (Manpages, 2008) where we put the semaphore. The second important consideration is that if no session daemon is available,

the user space tracer should wait passively in a separate thread, hence not altering the execution behaviour of the application. A `futex` object (Drepper, 2011) was chosen.

A `futex()` system call provides a way for a program to wait passively on a value at a given address. It can also use a method to `wake` anyone waiting on that value. This mechanism is typically used to implement locking scheme in a shared memory area. Thus, it provides a passive blocking call for the session daemon state variable and the contention dealt by the kernel.

Overall, there are two critical concepts for the wait/wake scheme:

1. Persistent memory area with a state flag (using a semaphore)
2. Waiting has to be passive (no CPU usage)

Figure 3.5 illustrates the data flow between the application and the tracer at this stage. The SHM area is created either by the user space tracer or the session daemon, whoever comes first, at a hardcoded path, and contains a `futex` object used to wake every process waiting on it.

The user space tracer *waits* on the futex and the session daemon, once spawned and ready for registration, notifies all waiting applications by atomically setting the state flag and *waking* the futex (`FUTEX_WAKE`).

After this notification, instrumented applications register to the session daemon. At any point in time, if the session daemon dies, the same process is done all over again. The user space tracer returns waiting on the global `futex` which is reset atomically by the session daemon when quitting. If an application cannot connect to a daemon and the state of the flag indicates to register, the application will reset it.

There is a potential race at the user space level when two applications try to create the SHM area. The kernel ensures (Love, 2010) that only one shared memory segment is created with the same path, so if one creation fails with an already exist error message, the user space tracer retries immediately to wait on the futex.

This design is important because it avoids starvation on the tracer side by using `futex` synchronization. The tracer is either waiting or registering. There is absolutely no window where it could wait forever. It would be unacceptable for an instrumented application to never register hence not be traceable. Moreover, this registration phase is only done once and before the `main()` of the application is called. Little extra time is added to the program execution 3.6.

Figure 3.5 shows that once the session daemon wakes the `futex`, all applications, which can be numerous, immediately try to register by connecting to a socket (ust sock) created by

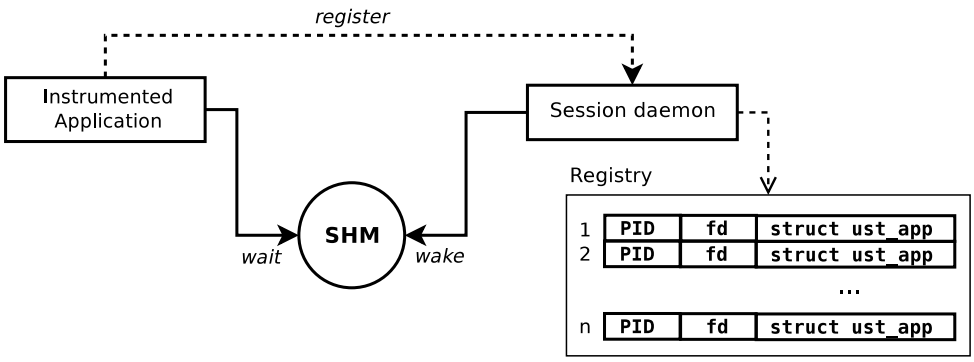



Figure 3.5 User space tracer registration

the session daemon and sending the registration data. The kernel allows us to queue multiple requests for connections with the `listen()` syscall. However, once accepted, handling the registration should be very fast.

Figure 3.6 illustrate the detailed scheme used to dispatch a registration to a thread pool without locks. Once the instrumented application sends its information, it is immediately enqueued in a wait-free queue provided by the URCU library (Desnoyers *et al.*, 2010) and the next registration waiting on the socket can be handled. The dispatcher thread is the next step.

The dispatch thread is using the dequeue blocking call of the wait-free queue and, once the node is popped, it is written on a `pipe` (Rochkind, 2004) (a fast data IPC available for Linux, see section 3.6 for detailed benchmark). There is one pipe per thread in the thread pool and the dispatcher is going in a round-robin to assign the request to a thread. The registration request is the same size and time regardless of the application so the dispatch policy is pretty simple. Once the registration is completed, i.e. adding an entry in the lockless registry 3.5.2, a registration done packet is sent back and the socket is kept open and used for later commands.

This socket is added to a central application management thread which polls every user space socket and monitors events. This is how the session daemon can detect an unregisteration. If the socket is closed on the application side, the session daemon picks it and handles the cleanup. This mechanism is particularly interesting for two reasons.

First, for any application dying unexpectedly, for instance a segmentation fault, the kernel closes the socket automatically so the *in-process* library (tracer) does not have to notify the session daemon (and in this example won't be able to do so anyway).

Secondly, command synchronization is based on the availability of the socket. Any command failing on the user space tracer (with a write error on the socket) automatically cleans

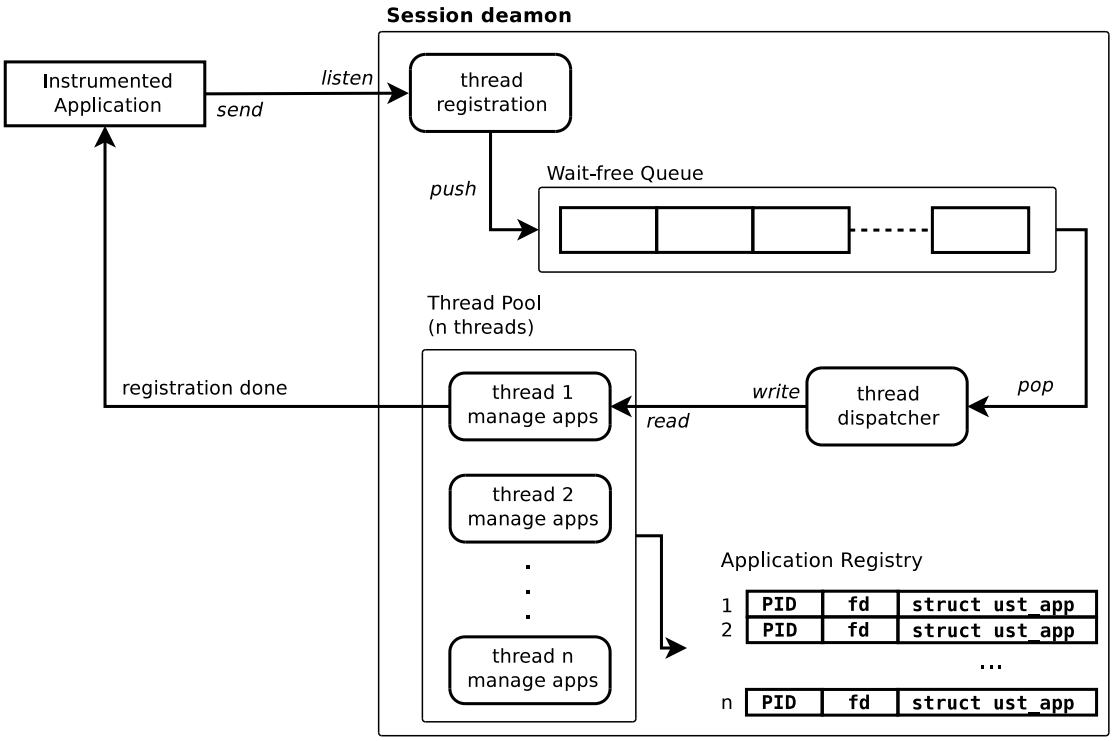



Figure 3.6 Session lock with the lockless hash table issue

up the application session registry of newly created data structure protected by RCU mechanisms. It is however very important to close the socket on the session daemon side after releasing application and registry data structure memory, or else an application could register during that time, and the socket number be reused. This would create incoherent data in the registry having a session assigned to the application but non existent in the tracer.

By monitoring this socket, we are able to remove synchronization primitives between the user and the tracer since it is correct, by design, for the command to fail on the tracer side, even if the data is coherent on the session daemon.

### Tracing registry

The tracing registry stores tracing sessions and application information using lockless data structures. Figure 3.7 is a representation of the registry tree for tracing session objects 3.5.1.

A tracing session contains two tracer types, the first level nodes of the registry hierarchy, with the tracing session itself being the root node. Those nodes contain per domain channel hash tables. For example, the `UST_PID` domain is a hash table indexed by PID and each bucket contains a hash table of channels. The `UST` and `KERNEL` domains are actually a single

structure containing a hash table of channels. Indeed, those domains are global and only one element is possible.

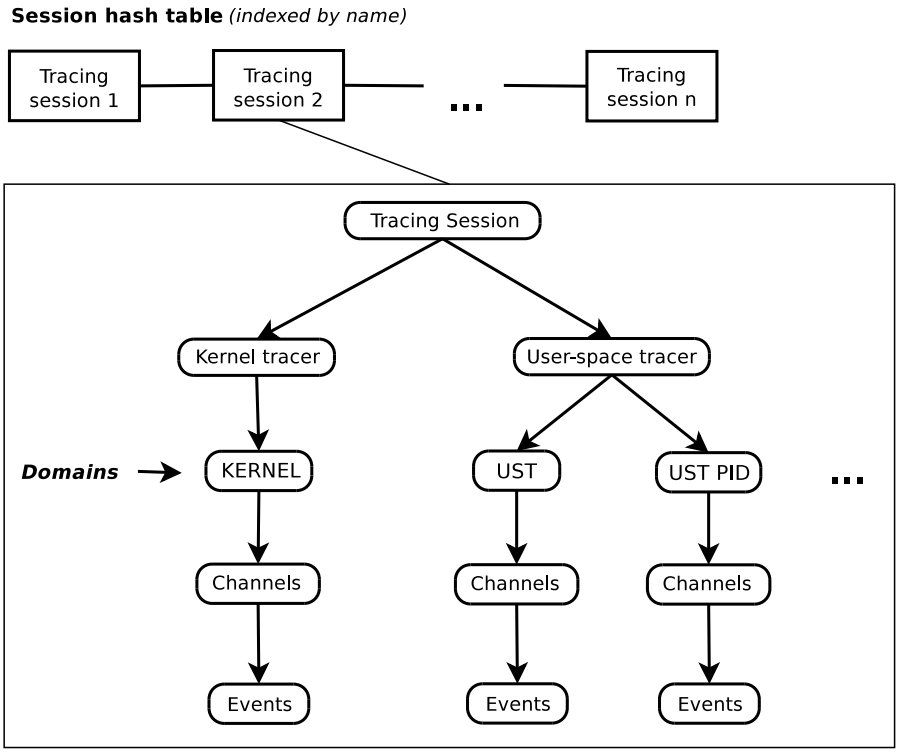



Figure 3.7 Tracing registry

The main goal of this structure is to be efficient for lookups and insertions. Each user command specifies at least a session name and a domain. Lookups for the session, a channel and an event are all $O(1)$. Thus, every client command is efficiently handled.

The insertion process is trivial, beginning with a lookup by key given by the user (Ex: channel name), to see if the object already exists and adding it to the right hash table found using the tracing session name and domain. The cost of adding an element is basically the time to hash the key, see section 3.6 for performance results.

However, a special use case arises for the kernel tracer. Channels are allocated on a per CPU basis, meaning that the number of data structures allocated is set to the number of enabled CPUs. Linux supports CPU hotplug, the kernel then informs the session daemon of added or removed CPUs, and the channel hash table has to be updated accordingly. We currently use a per-session `pthread_mutex` (Rochkind, 2004) to synchronize the channel hash table between the thread handling client commands and the thread handling CPU hotplug. As future work, the user space lockless notification mechanism developed during this research, explained in section 3.5.2, will be implemented.

The tracing registry also keeps track of registered applications. With LTTng UST 2.0 tracer (Desnoyers, 2012), applications register at startup with the session daemon, trying to connect to a socket and send information such as UID, GID, PID and library version used to validate the compatibility of the tracer against the session daemon. That bidirectional Unix socket (Linux, 2008) is kept open for future tracing commands requested by the user.

The transmitted information is stored in an application structure (See appendix A for the code reference) which is kept in **two** lockless hash tables where one is indexed by PID and the second one is indexed by socket file descriptor number. Upon registration, we get the PID of the application and a new socket file descriptor value. An `add_unique` operation is done using the PID as key to insert the application into the registry. When an application unregisters, the only notification we have is the socket application being closed. Therefore, the session daemon needs to be able to find the application using two different informations, PID and socket number. In a previous implementation, the second table simply mapped from socket to PID, leading to a race when a process was removed between the access to the socket to PID table and the access to the PID table, as shown in figure 3.8. The important point is that every lookup to the registry has to be done in a single operation to avoid such races in this lockless design.

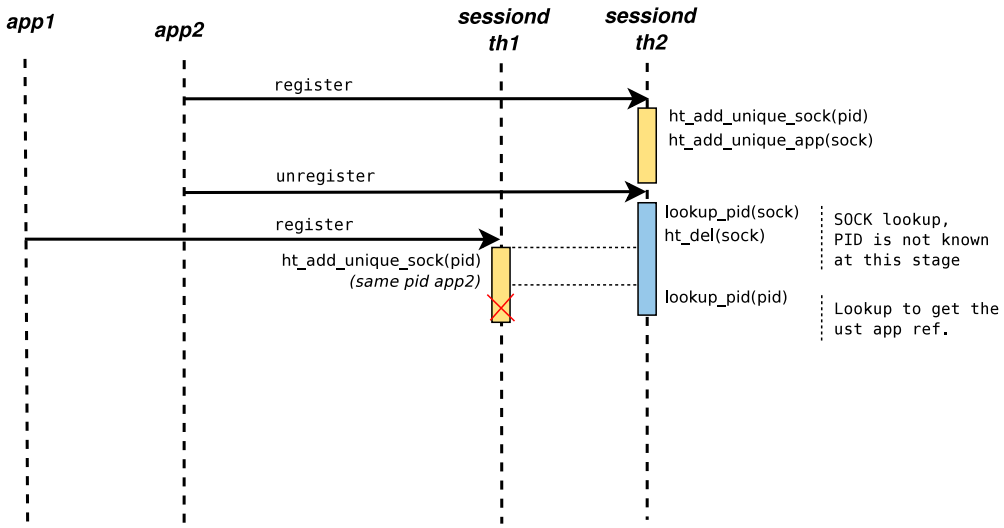



Figure 3.8 Two lockless hash table node

This registration process is of prime importance, creating the user space tracer *rendez-vous* point allowing the session daemon to provide features that the tracer itself cannot provide. It allows the user to list what are the available applications to trace.

Furthermore, for user space tracing, events that measure and record bootstrap procedures for an application are extremely common. With the tracing registry, all events are

first defined in the session daemon and then dispatched to the appropriate domain (tracer). This enables preregistered channels/events for a session, before the application has started. Since a tracing session is independent of the tracer lifetime, those pending events are automatically enabled on the tracer when it becomes available (by registering).

### Multiple tracing sources case

User-space tracing is more involved since, unlike the Kernel, we have multiple tracing sources (applications). This brings different synchronization issues between client commands and application commands. The typical scenario is:

1. Tracing is started
2. The enable-event command, when completed, assures the user that the data will be recorded if the user space tracer hits the event.

Figure 3.9 shows the two possible race conditions that can happen where the enable event begins **before** the registration and the second one begins **after**.

For example, a script could be enabling several events, while in parallel an application to trace would be started. Several events would be enabled before the application starts and registers with the session daemon, while others would be enabled after the registration.

The two cases are valid and have to apply to the registering application. This example can be extended to all commands and illustrates the concept of data coherency between the user and the tracer.

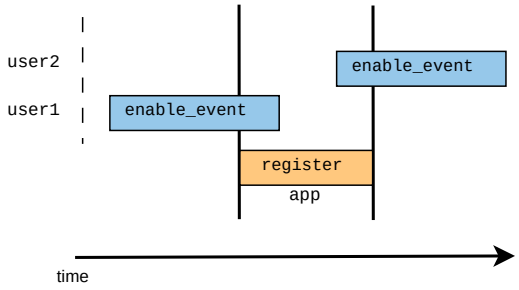



Figure 3.9 Possible race with register before

In order to maintain a good performance, even with a large number of registering applications, an efficient synchronization mechanism, shown in figure 3.10, was developed to address the previous race conditions. Every *list* of objects is actually a lockless hash table from the user space RCU library (Desnoyers *et al.*, 2010). Every reading and deletion uses

RCU (McKenney et Walpole, 2007), thus completely eliminating the use of locks for every operation, as long as we have a single writer.

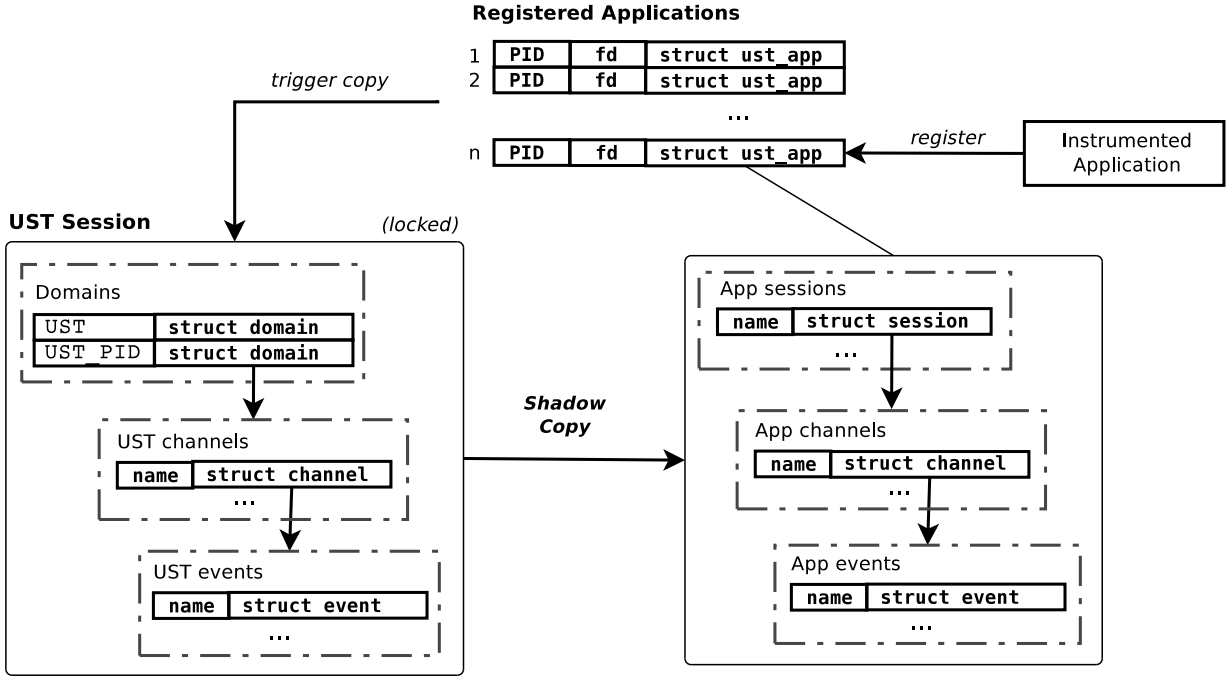



Figure 3.10 Lockless shadow-copy mechanism on application registration

When an application registers, it is quickly added to the registered application hash table. It then triggers a *shadow copy* of all UST sessions of all tracing sessions (from the registry) to its *application session* structure. The *application session* structure thereafter contains all applicable sessions, channels and events for the application, which can then be activated accordingly. The UST sessions thus represent user tracing commands, while the *application session* represents the application tracing state.

Figure 3.11 illustrate the concept of shadow copy on a user command. The UST session reference is acquired, modifications are done on that session and the shadow copy is triggered for each user space application session. An important point to understand is that every addition, modification or deletion is first done onto the UST session and then applied to the application session. Upon registration, the UST session hash table is used to trigger the shadow copy.

The last element to examine is how to modify a tracing session in a multi-threaded environment. Multiple users can modify the same session concurrently. Many concurrent commands may be issued using `lttng` command line, modify the tracing session information and trigger actions in application tracers. At this time, lttng-tools does not handle client commands using a thread pool scheme, but its synchronization model was designed and

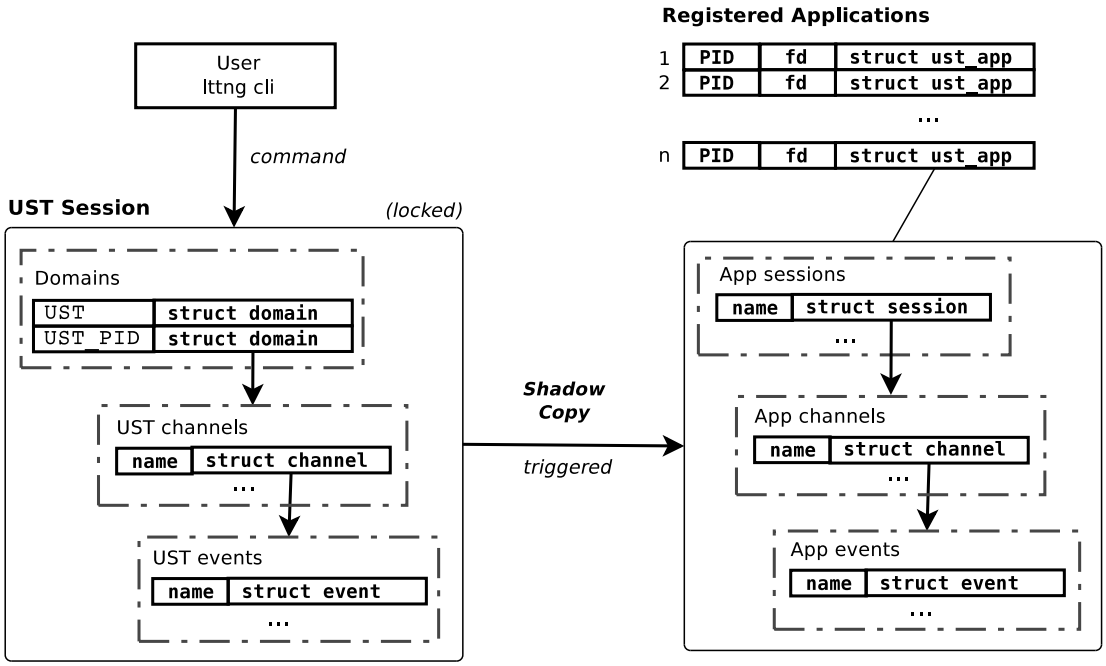



Figure 3.11 Lockless shadow-copy mechanism on client command

implemented to handle concurrent access.

RCU cannot handle our use case with multiple writers. Therefore, to prevent session structures from being modified concurrently, a per-session mutex was added. For each modification to a tracing session, the mutex is locked until every action is completed. However, it does not prevent concurrent writing to the session list. However, by using a RCU hash table for the session list, we can add and remove nodes without problem, as long as the sessions are modified sequentially between commands, and releasing memory is done inside a RCU critical section. LTTng-tools takes full advantage of RCU mechanisms by removing the node from the hash table without a lock, modifying it and adding it back.

Yet, there is still one remaining potential issue shown in figure 3.12. After getting a reference to a session (from the hash table), the session must be removed from the hash table to make sure that no other writer modifies it during the destroy process. Writers already with a reference to the session are protected during the destroy process because of the per session mutex. Thus, the race condition occurs between the lookup and the lock of the second thread, where the first thread can destroy the session during that interval (but not `free()` since it must be done in a RCU critical section).

Fortunately, this scenario is resolved by acquiring the session mutex before the hash table deletion and by doing a second lookup in the hash table to validate if the session deletion occurred during the race window. Table 3.1 shows sequentially how this scheme works where

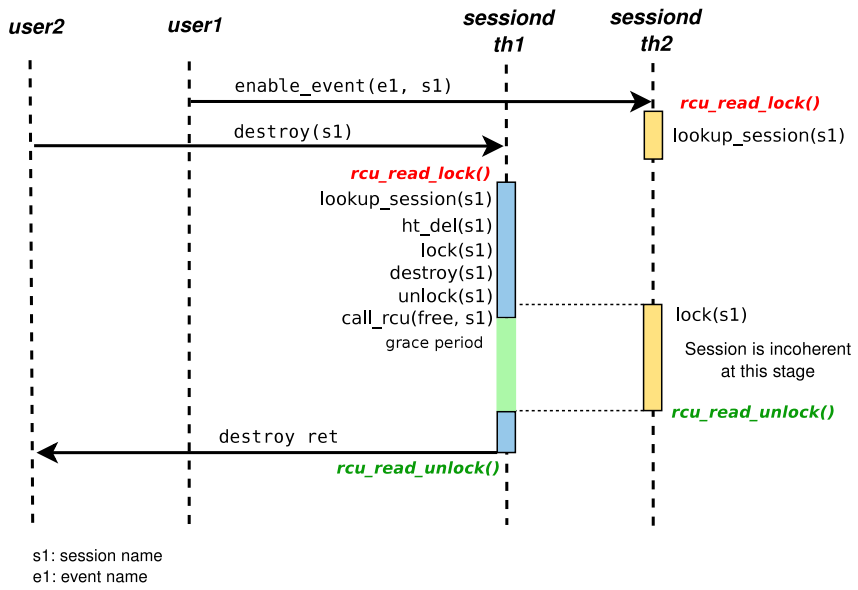



Figure 3.12 Session lock with the lockless hash table issue

each column is a different thread doing modification and removal concurrently (th1 and th2 are from 3.12).

Table 3.1 Scheme to avoid race condition between look up and lock

| Modify (th1) | Removal (th2) |
|---|---|
| `lookup()` | |
| | `lookup()` |
| | `lock_session()` |
| | `ht_del()` |
| | `unlock_session()` |
| | `call_rcu(free session)` |
| `lock_session()` | |
| `lookup()` | |
| *session unavailable* | |

There is also the possibility of using a simple *deleted* flag on the node and testing it atomically instead of acquiring a mutex. However, it was implemented that way to take advantage of the `pthread_mutex_lock` blocking call.

In summary, the tracing registry is the backbone of LTTng tracing, being a *rendez-vous* point for all tracing components, thus ensuring data coherency between the user, the tracers and the consumers.

## 3.6 Experimental results

This section presents the experimental results of all lttng-tools mechanisms. Section 3.6.1 shows the different benchmarks done, as of today, on the lttng-tools 2.0 stable version:

- User space tracer notification
- User space tracer registration
- Performance baseline

This section also includes performance results on studied Linux IPC. Those results are the performance baseline of the implementation and a discussion follows on possible avenues to improve this baseline.

Finally, section 3.6.2 compares our work to studied user space application synchronization mechanisms presented in section 3.3.

### 3.6.1 Benchmarks

First, Table 3.2 describes the test setup hardware used for the benchmark. After that, for each subsection, the methodology is explained first and results are presented in a table.

Every measurement was taken using the precise cpu cycle count before and after each tested section. See appendix B to see how the cpu frequency is measured before running the benchmarks. For the IPC section, the Linux command `time` is also used for comparison.

#### Linux IPC

As aforementioned, this study analyzed the different possible IPCs (Kay A. Robbins, 2003) of the Linux operating system in order to determine the fastest and most efficient for

Table 3.2 Test setup specification

| | |
|---|---|
| CPU | Intel Core i7 920 @ 2.67GHz |
| RAM | 6 GB |
| OS | Linux ubuntu 10.04.4 |
| Kernel | 3.2.0 |
| Version lttng-tools | 2.0-stable |
| Version lttng-ust | 2.0-stable |
| Version libc6 | 2.11.1-0ubuntu7.8 |

our application.

Shared memory area is of course the fastest IPC between processes since, once initialized, there is no system call to access the data. Nevertheless, this requires more synchronization, often ending up using a system call to deal with contention.

Asynchronous bidirectional communication between threads and processes is crucial for lttng-tools. For this reason, we experimented with pipes and sockets, testing outbound and inbound data transmission. Tables 3.3 and 3.4 show the write and read average time for the *pipe* IPC along with the standard deviation. Tables 3.5 and 3.6 present the send and recv average time. The standard deviation is also available.

Benchmarks were run 1000 times for each with different message sizes ranging from very few bytes (16) to four times the size of a Linux memory page of 4096 bytes. For each result, the received data is validated against the sent data.

The overall difference between those two mechanisms are shown in figure 3.13 and 3.14.

Table 3.3 `write` to pipe

| Bytes | Time | Deviation |
|---|---|---|
| 16 | $3.3197\times10^{-6}$ sec. | $0.16344\times10^{-6}$ sec. |
| 1024 | $3.4067\times10^{-6}$ sec. | $1.09235\times10^{-6}$ sec. |
| 4096 | $3.4127\times10^{-6}$ sec. | $0.24667\times10^{-6}$ sec. |
| 8192 | $3.9786\times10^{-6}$ sec. | $0.31152\times10^{-6}$ sec. |
| 16384 | $5.5347\times10^{-6}$ sec. | $0.17899\times10^{-6}$ sec. |

Table 3.4 `read` from pipe

| Bytes | Time | Deviation |
|---|---|---|
| 16 | $4.1076\times10^{-6}$ sec. | $0.4876\times10^{-6}$ sec. |
| 1024 | $4.2581\times10^{-6}$ sec. | $0.4925\times10^{-6}$ sec. |
| 4096 | $4.6689\times10^{-6}$ sec. | $0.0858\times10^{-6}$ sec. |
| 8192 | $7.5881\times10^{-6}$ sec. | $0.6682\times10^{-6}$ sec. |
| 16384 | $12.1067\times10^{-6}$ sec. | $2.9066\times10^{-6}$ sec. |

The croocked line in figure 3.13 and 3.14 which occurs at 4096 and 8192 are page faults triggered by the kernel hence creating a longer time to manage the data.

These results demonstrate the very thin difference between the two. In addition, Unix sockets allow two key features that are used across the lttng-tools code base: passing process

Table 3.5 `send` to socket

| Bytes | Time | Deviation |
|---|---|---|
| 16 | $2.3662\times10^{-6}$ sec. | $0.26949\times10^{-6}$ sec. |
| 1024 | $2.4888\times10^{-6}$ sec. | $0.09812\times10^{-6}$ sec. |
| 4096 | $2.7906\times10^{-6}$ sec. | $0.07993\times10^{-6}$ sec. |
| 8192 | $4.1098\times10^{-6}$ sec. | $0.18246\times10^{-6}$ sec. |
| 16384 | $6.0743\times10^{-6}$ sec. | $0.26255\times10^{-6}$ sec. |

Table 3.6 `recv` from socket

| Bytes | Time | Deviation |
|---|---|---|
| 16 | $3.9375\times10^{-6}$ sec. | $0.26938\times10^{-6}$ sec. |
| 1024 | $4.2832\times10^{-6}$ sec. | $0.12567\times10^{-6}$ sec. |
| 4096 | $4.6800\times10^{-6}$ sec. | $0.31030\times10^{-6}$ sec. |
| 8192 | $9.2137\times10^{-6}$ sec. | $0.39677\times10^{-6}$ sec. |
| 16384 | $14.5910\times10^{-6}$ sec. | $1.99072\times10^{-6}$ sec. |

credentials and file descriptors over the socket. Using sockets is therefore a good choice for bidirectional communication, because of these very useful extra features.

### UST notification

This performance measurement was done 1000 times and the average time of all runs is presented. The notification process implies more fine-grained measurements.

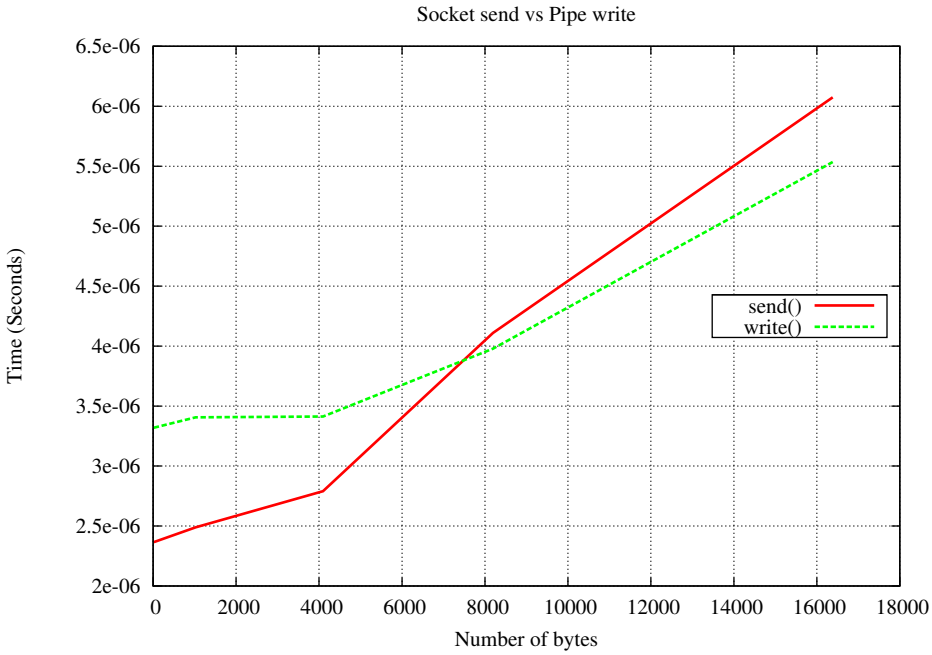
The context of this benchmark is that the session daemon starts and notifies applications. For the session daemon part, table 3.7 shows the step by step procedure and breakdown in time. The following results show the notification procedure on the session daemon side only.

### UST registration

This benchmark was run **1000** times over an eight hour period and measure each steps of a single instrumented application registration. Table 3.8 break down the time step by step for each important registration procedure (Refer to section 3.5.2 to understand the each step).

We end up with a baseline of 0.1526 millisecond on average for one single application registration. At this point in time, the lttng-tools session daemon does not handle application

Figure 3.13 Socket send() vs Pipe write()




registration using a thread pool. However, since lockless data structures are used to add the application to the registry, the increase in time, for a thread pool design, should only appear at step 3 where the dispatcher thread would have to choose an idle worker thread.

Note step 3 which is two times faster than the measured `read()` for a pipe in section 3.6.1. This is due to kernel page caching. The same test was run but dropping caches just before the read operation. The values are then very close to the section 3.6.1 measurements.

Step 5 is a back and forth communication with the application, since a `REGISTER_DONE` acknowledgement is sent back by the application.

### Performance baseline

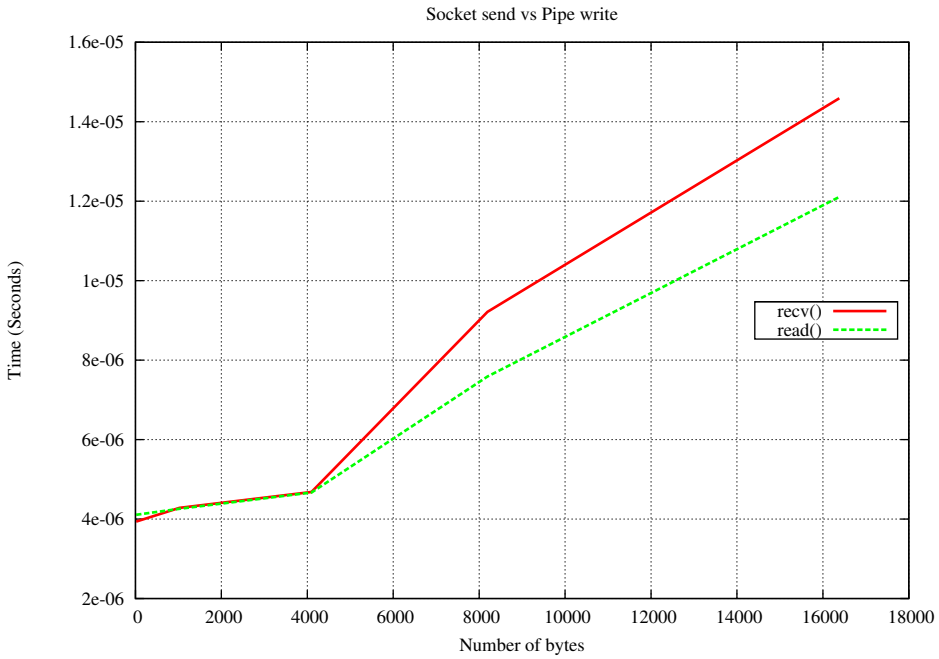
To get a performance baseline, we have created an experiment which runs $n$ instrumented processes concurrently and enable tracing on each of them. This experiment was run 1000 times for each $n$ value.

We have measured the memory consumption before, during and after the experiment by sampling at a regular rate. CPU usage was also sampled.

For memory measurements, the real memory usage was sampled every 0.2 seconds using values in `/proc/PID/status` (`VmRSS` value). For CPU usage, the tool `top` was used, configured to sample a single PID.

The experiment is setup with the following lttng commands. The line `[experiment]` is

Figure 3.14 Socket recv() vs Pipe read()




when the tracer code is being run.

```
# lttng create nevents
# lttng enable-event ust_gen_nevents:tptest -u
# lttng start
[experiment]
# lttng stop
# lttng destroy nevents
```

The following experiment was run for user space tracing. Sampling began from `lttng start` up to the `destroy session`. Table 3.9 and 3.10 show the memory and CPU usage results respectively for each value of $n$. Each result is the average of the samples, averaged over the number of experiments. The before column means that the sampling occured before the test was launched and the rest can be explained the same way.

The results show that the CPU usage footprint on the system is very low and almost constant across workloads.

Table 3.9 shows approximately the memory footprint of a single application registering one event for every value of $n$. Looking at the difference between before and during the experiment and dividing it by $n$ we get an approximation of memory usage for a single application registration.

Table 3.7 UST notification time breakdown

| | Step | Time |
|---|---|---|
| 1 | Memory mapping for the shared page | $4.3458\times10^{-6}$ sec. |
| 2 | Setting read-only permissions | $4.6256\times10^{-6}$ sec. |
| 3 | Open shm and truncate it to fit a memory page | $9.6669\times10^{-6}$ sec. |
| 4 | Futex wake call | $4.9137\times10^{-6}$ sec. |
| **Total** | | $23.552\times10^{-6}$ sec. |

Table 3.8 UST registration time breakdown

| | Step | Time |
|---|---|---|
| 1 | Receiving and enqueue data | $36.394\times10^{-6}$ sec. |
| 2 | Dequeue and write to pipe | $11.564\times10^{-6}$ sec. |
| 3 | Read from pipe | $2.6511\times10^{-6}$ sec. |
| 4 | Add app to registry | $32.535\times10^{-6}$ sec. |
| 5 | Send register done | $69.441\times10^{-6}$ sec. |
| **Total** | | $152.58\times10^{-6}$ sec. |

$$(1475 - 1192)/n = 283 \text{ kB} \tag{3.1}$$

$$(8255 - 1192)/n = 70.63 \text{ kB} \tag{3.2}$$

$$(59936 - 1192)/n = 58.744 \text{ kB} \tag{3.3}$$

We end up with a memory footprint of less than 58 kilobytes per registered application since $n = 1$ shows the amount of memory needed for data structures handling application registration. Since the process event was enabled by the user, a shadow copy was triggered, increasing the memory usage. Also, channel streams are on a per CPU basis and contain a trace directory path of 4096 bytes. More cores, more memory.

### 3.6.2 Comparison

This section takes a look at the dispatching mechanism performance. Section 3.6.1 shows the time it takes, once an application has established a connection, to dispatch and handle

Table 3.9 Memory usage of lttng-sessiond (size kB)

| | Before | During | After |
|---|---|---|---|
| PROCESSES $(n = 1$ | 1196 | 1477 | 1210 |
| PROCESSES $(n = 100)$ | 1192 | 8255 | 1240 |
| PROCESSES $(n = 1000)$ | 1192 | 59936 | 4010 |

Table 3.10 CPU usage of lttng-sessiond (% System CPU time)

| | Before | During | After |
|---|---|---|---|
| PROCESSES $(n = 1)$ | 0.50 | 0.50 | 0.50 |
| PROCESSES $(n = 100)$ | 0.50 | 0.50 | 0.50 |
| PROCESSES $(n = 1000)$ | 0.50 | 0.58 | 0.60 |

the application registration.

Our case study was Apache 2.2 (Fielding et Kaiser, 1997). With the following results, we can confirm that our solution indeed works very efficiently. Indeed, our proposed implementation was even used to pinpoint possible issues with the dispatching mechanism of Apache.

### Apache 2.2

As mentioned in section 3.3.2, Apache relies on the kernel to resolve contention on a global mutex lock shared between threads. The dispatching time was measured using LTTng kernel tracing, since we cannot measure this in user space. The `pthread_mutex` implementation of libc uses the `futex` syscall to manage multiple threads locking a mutex or contention. By monitoring this system call, we can measure the contention time imposed by the kernel on multiprocessor machines and have a good estimation of the time it takes to assign a task to an Apache worker thread.

We first installed Apache on a Ubuntu 11.04 server and created a dummy web page. Here is the setup experiment.

1. Kernel tracing

   *The following commands enable syscall tracing and add to each event the PID, process name and TID so we can recognize the apache2 processes.*

   ```
   # lttng create apache
   # lttng enable-event -a -k --syscalls
   # lttng add-context -k -t pid -t procname -t tid -c channel0
   ```

```
# lttng start
[...]
```

2. Multiple client HTTP request
   *We used a script to make 10 requests simultaneously. Appendix C shows the small simple script used.*

Looking at the tracing results, we have to make sure that the `futex` system call measured is the correct one. For a mutex lock to return, the contention is resolved when a thread does an unlock. Here is an example of a `futex` call taken, from the trace to understand what is happening.

```
[...]
[13:35:28.093556882] (+0.000003038) sys_futex: { 2 }, { 6821, "apache2",
6792 }, { uaddr = 0x7FEF5EB31D10, op = 129, val = 1, utime = 0x1, uaddr2 =
0x7FEF5EB31D60, val3 = 67108865 }
[13:35:28.093568000] (+0.000011118) exit_syscall: { 2 }, { 6816, "apache2",
6792 }, { ret = 0 }
[...]
```

Here we have a `sys_futex` syscall made on the first line for PID 6821 with parent being 6792 (our main dispatch thread of Apache). The op value indicates that this call is actually doing a `FUTEX_WAKE`. Thus, some previous thread unlocked the mutex and now the kernel is dealing with contention for the other threads trying to lock the mutex.

The C library does actually more `futex` syscalls to handle this situation, increasing the total time significantly. However, we just want to compare the unlock/contention/lock mechanism.

The second line indicates the end of the `futex` syscall, which is immediately after. It shows that the exiting PID is 6816. This thread is then in control of the mutex lock critical section. We can also confirm that we are in fact dealing with a request being served and dispatched by looking at the following syscalls issued by Apache: `sys_gettimeofday` and `sys_getsockname`. The CPU number is displayed just after the system call name (Ex: {2}).

```
[13:35:28.093579552] (+0.000008049) sys_gettimeofday: { 2 }, { 6816,
"apache2", 6792 }, { tv = 0x7FEF4EB43CD0, tz = 0x0 }
[13:35:28.093580797] (+0.000001245) exit_syscall: { 2 }, { 6816, "apache2",
6792 }, { ret = 0 }
[13:35:28.093584705] (+0.000003908) sys_getsockname: { 2 }, { 6816,
"apache2", 6792 }, { fd = 10, usockaddr = 0x7FEF5EB6F3F0,
```

```
usockaddr_len = 0x7FEF5EB6F3D0 }
[13:35:28.093587079] (+0.000002374) exit_syscall: { 2 }, { 6816, "apache2",
6792 }, { ret = 0 }
```

After identifying the dispatch pattern in the trace, the offset between the beginning of the futex call and the exit (just after the timestamps in the parentheses) can be measured. Table 3.11 shows four requests, providing a good approximation of the dispatch time in seconds.

Table 3.11 Apache dispatch request time

| | Req 1 | Req 2 | Req 3 | Req 4 |
|---|---|---|---|---|
| Time | $11.118\times10^{-6}$ | $14.257\times10^{-6}$ | $16.578\times10^{-6}$ | $13.044\times10^{-6}$ |

Those requests are *lucky* ones since they were all handled by the same CPU, hence with pretty good performance results. This is even better than our dispatch mechanism, calculated with the sum of line 1 and 2 in table 3.8, ( 0.0004 sec.) including the `recv()` system call.

However, letting the kernel handle contention in a multithreaded environment can be costly. Indeed, it is possible for one thread on a CPU to unlock and another thread on an another CPU to lock. This causes a serious performance penalty to get the CPU caches coherent between the two CPUs. From the same trace, here is an example of the time penalty when bouncing between CPUs.

```
[14:35:49.744430680] (+0.000002175) sys_futex: { 2 }, { 6803, "apache2",
6792 }, { uaddr = 0x7FEF5EB31D64, op = 129, val = 389, utime = 0x0,
uaddr2 = 0x0, val3 = 182 }
[14:35:50.615251899] (+0.870821219) exit_syscall: { 3 }, { 6787, "apache2",
6787 }, { ret = 0 }
```

The migration between processors costs 0.87 seconds for the `futex` wake call. This result was confirmed by the `sched_switch` event being traced at the same time (here removed for brevity) and shows the CPU migration for the correct process.

It is important to understand that, even though this can happen, the Linux scheduler is optimized to avoid theses situations. Nonetheless, dealing with contention in user space can help circumvent this.

### 3.6.3 Discussion

The proposed tracing architecture, implemented in `lttng-tools`, is the first published working infrastructure that unifies tracing for user and kernel space under one component not being a kernel module. The ability to trace entirely in user-space gives to this approach a significant speed advantage.

One of the most widespread tool used to debug development code and production use cases is `strace` which takes advantage of the `ptrace` functionality. However, this comes at an important performance cost. With the previous performance results, we hope to provide equivalent functionality to `strace` at almost no performance cost, cutting the performance trade-off associated with tracing and improving the applicability of tracing to production usage.

## 3.7 Conclusion

We have presented the lttng-tools project which implements the synchronization mechanisms proposed for handling large scale tracing with multiple sources. There are three important processes explained which are the fast and efficient dispatching mechanism for application registration, the user space tracer notification, used to notify waiting applications to register to the session daemon, and the tracing registry data structure interactions.

Our proposed dispatching system resulted in good performance when dealing with a large number of registering applications and can easily be extended and used by programs dispatching a large number of requests to a thread pool. The use of lockless data structures came with synchronization challenges and largely drove the design and development of the tracing registry.

We are confident that the synchronization and lockless algorithms presented in this paper can be extended to a large set of use cases, from load balancer system to telecommunication workloads, where large number of requests are dispatched.

This study brought to life one of the core system of the LTTng 2.0 toolchain and provided a new set of features for Linux tracing. Efforts were spent for bringing better usability to users and to system administrators in large in data centres.

# CHAPTER 4

# GENERAL DISCUSSION

This chapter focuses on complementary work done during this research on the lttng-tools project and user space tracing.

Section 4.3 presents the work done on performance measurements of the lttng user space tracer 0.x and how the scalability was improved significantly. There improvements formed an important portion of the improvements leading to version 2.0.

## 4.1 Thread pooling

As a reminder, thread pools are a set of worker threads where all resources are allocated preemptively and used during the program lifetime to help serve efficiently large number of requests. The registration process and client commands management can be handled with a thread pool. The current `lttng-tools` implementation does not currently use this.

However, here are some important considerations to take into account in order to achieve thread pooling for managing registration and client commands.

For the registration, the application registry has to be protected against multiple writers since RCU cannot guarantee coherency through multiple writes. Insertion has to be in a *critical section*. Since this registry was designed using a lockless hash table, the insertion cost of one application is basically $O(1)$. Moving to a multithreaded registration scheme would likely speed up the process, since insertion is only a fraction of the total cost the thread would have to pay which is $O(n)$ where $n$ is the number of threads.

Secondly, threading client commands is non trivial. The model proposed is based on the fact that the tracing session is only modified through one vector (the client) and is protected by a `mutex` against modifications, for instance two racing user commands modifying a given session. Creating a thread pool here makes sense to speed up the process so the session daemon could handle more user commands concurrently.

A more fine-grained locking, i.e. using locks on channels and events instead of the whole tracing session, can be a solution to increase the performance of multiple users modifying the same session. The most important aspect of our synchronization model is that the session is only modified by the user. While still satisfying this condition, better locking could be used

to limit contention on tracing objects.

There is also the question of how many threads are needed to get the best efficiency out of our two use cases. One known optimization would be to use one thread per CPU, making sure each thread is not bounced between cores. However, this solution is limited by what the thread does exactly. We use asynchronous blocking IPC (sockets) to communicate, which creates a problem if the thread not only waits for the incoming data but also sends back information. Delays can incur large wait periods on either the incoming or outgoing data. Using a per CPU thread, this can block the CPU. The dispatcher can starve quickly not being able to find a thread to assign the request due to I/O delay.

For the client command manager, a thread pool on a per CPU basis is less than ideal for the aforementioned reason. The same applies for the application registration thread, since it has to reply on the application to notify the completion of the registration.

This is why the Apache project uses a default value of 25 threads per listener process, since it relies heavily on network I/O and starvation has to be avoided.

## 4.2 Network streaming

Network streaming is another aspect considered but not covered throughout this research. We briefly discussed the challenges and basic design work done recently to support trace network streaming.

Communication over the network becomes inevitable when the client and the session daemon have to be able to send and receive actions between the host and target systems. A network consumer is thus needed to handle the reception of data (streaming) and make sure it is written to disk in the correct order as well. Network transport layer can offer such guarantee (ordering) but at the cost of performance (TCP vs UDP).

When communicating between systems, authentication is an additional security requirement. When tracing on a local machine, user credentials validate if the user is allowed to talk to the session daemon or trace an application. On a remote machine, some kind of authentication mechanism is needed to avoid unauthorized remote users controlling tracing. Here are the factors we need to consider for network communication.

- Transport layer (Ex: TCP, UDP)
- Integrity
- Authentication
- Data protection

Extending those new constraints to the current model, synchronization has to be designed in order to guarantee data integrity (trace data received during streaming) and interaction

between remote sessions (remote user versus local user). Moreover, the data and control paths should be separated such that one bad command does not cause the streaming trace to stop or break down.

The transport layer could change, hence providing packet ordering on reception is needed. Thus, an extra protocol is needed on top of tracing data to provide minimal information to the remote consumer on the ordering scheme and the associated session information.

The authentication part is a more technical aspect but that can be fulfilled using the SSH protocol (Ylonen *et al.*, 2006), providing an encrypted tunnel for the control path and authentication on the remote machine.

As for data protection, this question has not been studied and is mentioned as future work in section 5.3.

## 4.3 UST 0.x scalability

Interesting work was performed to improve the scalability of the user space tracer 0.x made by Pierre-Marc Fournier (Fournier *et al.*, 2009). First, the tracer performance was measured to get a baseline for an event hit by the application and its overall impact. The following results and tests were made on version 0.11 and used the same setup as describe in section 3.6.

This tracer had three different tracing mechanisms to record data which are:

- `trace_mark` (using marker technology (Corbet, 2007))
- `trace_mark_tp` (using a marker inside a tracepoint)
- `ltt_specialized_trace` (tracepoint with custom probe)

The performance tests consisted of running 1000 times a simple single threaded program recording 5 million events for each tracing mechanism. The CPU cycle counter was sampled at the beginning and end of the event loop using the *rdtsc* (Intel, 2010). The time was recorded and the test was rerun again for 1000 iterations. The average was computed, providing the baseline time of an event.

At that point, running the same test again but without tracepoints gave us the normal execution time of the loop. The difference between them, divided by the number of events, got us the results found in table 4.1. Those results were presented at LinuxCon North America in 2010 [1].

1. `https://events.linuxfoundation.org/events/linuxcon`

| Mechanism | Time |
|---|---|
| Trace mark | 247 ns / per event |
| Tracepoint marker | 271 ns / per event |
| Custom probe | 189 ns / per event |

Table 4.1 UST 0.x benchmark

The user space tracer 0.x was designed to be scalable across CPUs using per CPU buffers. However, running those tests concurrently, generated a disappointing scaleup, 3 to 4 times the single threaded time per event.

Thus, we profiled the entire tracer to understand the problem. We investigated and discovered a large number of L1 and L2 cache misses where the tracepoint information was accessed (`marker_probe_cb`). Using `oprofile`[2], we were able to isolate the above issues.

The following is taken from an experiment run 100 times which ran 8 threads, each generating 50 million events.

```
                <L2_RQSTS, L1D_CACHE_LD, DTLB_LOAD_MISSES, CPU_CLK_UNHALTED>
marker_probe_cb     : ['97.15989', '93.84391', '76.53719', '77.41132']
```

We see here that the `marker_probe_cb` function is responsible for 93.84% L1 cache misses. It is the primary function to access tracepoint information.

Our tracepoint data structure gets in the CPU cache for any tracing related action on that processor. However, if the data is smaller than the cache line size (CPU specific), other objects can share the same line which can be accessed by other CPUs, hence creating *false sharing*. This may cause a back and forth cache line exchange between CPUs, which is very costly. This behaviour is known as *cache line bouncing*.

Even having per CPU buffers, and using TLS (Tread Local Storage) variables, sharing data between CPUs on a single misaligned cache line causes severe scalability issues. Knowing what data structure was bounced between CPUs, we added this simple patch to the code to align those structures to a cache line.

```
#define CAA_CACHE_LINE_SIZE 128 /* Defined in the Intel manual */

#define ____cacheline_aligned __attribute__((aligned(CAA_CACHE_LINE_SIZE)))
```

The trace became fully scalable on SMP systems meaning that we had the same event time shown above using 8 threads on an 8 core machines.

2. `http://oprofile.sourceforge.net`

# CHAPTER 5

# CONCLUSION

This chapter presents the conclusion of this research. The proposed tracing architecture and the lttng-tools project are first summarized. Then, some limitations of the current implementation are presented. Finally, we discuss possible improvements as future work.

## 5.1 Summary of the work

This main accomplishment presented here is the unified tracing architecture, combining user and kernel space control, and enabling the implementation of the `lttng-tools` project. It provides a command line user interface, a tracing control library, user and kernel tracing consumers and, the pivotal part of this architecture, the session daemon.

We have presented a tracing registry and algorithms that provide lockless interactions. This registry enables tracing sessions and aggregates user and kernel tracer information under one umbrella. Moreover, this registry is extended to registering applications, allowing user space tracing to record early event(s) during the bootstrap process, and trace events to be pre-enabled before the program lifetime. With registration, users are also able to list available traceable applications.

The notification process of waiting applications is also an important realization. Using a shared semaphore (implemented with `futex` and `SHM`), we were able to address race conditions on registration and insure that no starvation occurs on the application side (user space tracer). This scheme also enables applications to register in any state of the runtime, i.e. the program continues to work even if the session daemon is not available or is restarting.

Finally, we proposed a fast dispatch mechanism to handle application registration which can possibly be extended to thread pooling and larger workloads. We have shown that the CPU usage on the system is quite low during that process. This design takes advantage of multi-processor systems by creating three different processes to optimize the request dispatch and avoid wait periods on Linux IPC or I/O.

## 5.2 Limitations

Since the model allows to enable events on non registered applications, when the tracer registers, all tracing sessions are checked for *pending* events and enabled on the tracer side if it applies. This process takes the lock on the global session list to stop any modification and iterate. Assuming a large number of applications registering at the same time, this causes an important latency on the client side, since the global list is locked. Consequently, if the client request is very long, it will penalize every application.

The per session `mutex` is definitely a bottleneck to performance. Fine-grained locking could be done to address such problem. This would require precise measurements and synchronization checks.

The proposed model was not validated on other user space domains such as per PID events. The problem with this domain is that a PID can be reused for two different applications. If the tracing session has multiple events and channels enabled for a specific PID, if the application dies it is detected and the shadow copy is cleaned up. However, on a per PID basis, we would also need to clean the tracing session which only the client side can do securely in the current synchronization model.

## 5.3 Future work

As short term future work, one possible improvement would be to implement a thread pool design, for both application registration and user commands management, and validate its scalability.

The previous issues on per PID tracing is a more complex problem with the current scheme. Nonetheless, it would be very useful to allow `LTTng` to behave like `strace`.

The data protection issues are also important. There are mostly two ways to approach this problem. Either the transport layer is the secure channel or, upon extraction, the data itself is encrypted.

Furthermore, network streaming and remote control is still to be investigated. This would require to at least add one thread in the architecture, which will potentially bring synchronization issues and an in-depth review of the underlying algorithms.

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# APPENDIX A

# LTTng-Tools session code snippet

## Tracing session code

Listing A.1 **lttng-sessiond/session.h**

```
/*
 * This data structure contains information needed to identify a tracing
 * session for both LTTng and UST.
 */
struct ltt_session {
    char name[NAME_MAX];
    char path[PATH_MAX];
    struct ltt_kernel_session *kernel_session;
    struct ltt_ust_session *ust_session;
    /*
     * Protect any read/write on this session data structure. This lock
     * must be acquired *before* using any public functions declared
     * below. Use session_lock() and session_unlock() for that.
     */
    pthread_mutex_t lock;
    struct cds_list_head list;
    int enabled;    /* enabled/started flag */
    int id;     /* session unique identifier */
    /* UID/GID of the user owning the session */
    uid_t uid;
    gid_t gid;
};
```

# UST application code

Listing A.2 **lttng-sessiond/ust-app.h**

```
/*
 * Registered traceable applications. Libust registers to the
 * session daemon.
 */
struct ust_app {
    pid_t ppid;
    uid_t uid;              /* User ID that owns the apps */
    gid_t gid;              /* Group ID that owns the apps */
    int bits_per_long;
    int compatible; /* If the lttng-ust tracer version does not match the
                       supported version of the session daemon, this flag is
                       set to 0 (NOT compatible) else 1. */
    struct lttng_ust_tracer_version version;
    uint32_t v_major;     /* Verion major number */
    uint32_t v_minor;     /* Verion minor number */
    char name[17];        /* Process name (short) */
    struct lttng_ht *sessions;
    struct lttng_ht_node_ulong pid_node;
    struct lttng_ht_node_ulong sock_node;
};
```

# APPENDIX B

# CPU frequency acquisition code

## CPU frequency sampling code

Listing B.1 **benchmark/benchmark.c**

```
1  cycles_t get_cycles(void)
2  {
3      /*
4       * URCU macro using the cpu cycle counter:
5       *    #define rdtscll(val)                                        \
6       *      do {                                                      \
7       *           unsigned int __a, __d;                               \
8       *           asm volatile("rdtsc" : "=a" (__a), "=d" (__d));      \
9       *           (val) = ((unsigned long long)__a)                    \
10      *              | (((unsigned long long)__d) << 32);              \
11      *      } while(0)
12      */
13     return caa_get_cycles();
14 }
15
16 uint64_t get_cpu_freq(void)
17 {
18     struct timezone tz;
19     struct timeval tvstart, tvstop;
20     cycles_t c_before, c_after;
21     unsigned long microseconds;
22
23     memset(&tz, 0, sizeof(tz));
24
25     gettimeofday(&tvstart, &tz);
26     c_before = get_cycles();
27     gettimeofday(&tvstart, &tz);
28
29     sleep(1);
30
31     gettimeofday(&tvstop, &tz);
```

```
32      c_after = get_cycles();
33      gettimeofday(&tvstop, &tz);
34
35      microseconds = ((tvstop.tv_sec - tvstart.tv_sec) * 1000000) +
36          (tvstop.tv_usec - tvstart.tv_usec);
37
38      return (uint64_t) ((c_after - c_before) / microseconds);
39  }
```

# APPENDIX C

# Apache tests

## Apache test script

```
for i in ‘seq 1 10‘; do
wget -o /dev/null -b http://OUR_SERVER/index.html -O /dev/null;
done
```

# APPENDIX D

# Command line interface

## Command line interface

During the design and architectural phases of LTTng 2.0, the usability was one of the motivation behind the new version. Mainly, the 2.0 version had to unify the user space tracer and kernel tracer (and possibly more in the future) under one control tool. This is why the concept of *event*, explain in section 3.5.1, was introduced along with domains.

With the LTTng 0.x version (both kernel and user space tracer), there was two distinct programs used to control those tracers which are respectively *lttctl*, part of the ltt-control project, and *ustctl* integrated in the UST project (Fournier *et al.*, 2009). Now, the 2.0 version brought to life the session daemon which is, as a reminder, the central registry and *rendez-vous* point for all tracing sources and users. We needed a command line interface to handle user inputs and interact directly with the session daemon.

Moreover, a single command line interface is not enough for today use cases. It is not uncommon, as of today, that an instrumented application control itself tracing actions. Also, third part application managing tracing of large number of applications and systems is an important use case to support. Only using the `lttng` command in scripts or executing it at each action inside source code is not efficient nor portable.

This is why we designed a control library called *liblttng-ctl* which provide an API for every possible actions and features supported by the tracers and session daemon. The `lttng` command was built on top of it.

### lttng command

Mention earlier, the usability, for user experience and ease of use, was studied looking at three possible Linux user interfaces commonly used.

1. Arguments and options for all LTTng features like so:

```
$ lttng --create my_session
$ lttng --enable-event --kernel --name sched_switch
$ lttng --start
```

2. Provided shell **inside** a Linux shell (bash):

```
$ lttng
lttng> create my_session
lttng> enable-event sched_switch --kernel
lttng> start
[...]
```

3. Command-action combo on the command line (like the version control software git [1]

```
$ lttng create my_session
$ lttng list --kernel
[listing kernel events]
$ lttng enable-event sched_switch --kernel
$ lttng destroy my_session
```

The proof of concept of lttng-tools was originally designed using the UI number one and was a disaster as more features came in. As of today, the LTTng project as more than 14 different available features and more than 50 different options applicable on those features. Not only the first UI is very difficult to implement correctly by handling all possible command line arguments and options but it is also pretty difficult for the user to know what to use.

The second UI studied has almost the same *work flow* as the third one. However, the real problem is non-interactive user interaction. The Linux default shell, `bash`, comes with a scriptable language and makes the interaction really *organic* for users. With a home made shell has to come with functionnalities to make interactions easier from the Linux shell in order to support automatic user scripts managing `lttng` commands. The GPG [2] project has a shell like that but provides the same functionnalities with command line options (1). This is double the work and is an unnecessary development burden.

Finally, the third UI was the approach we chose. The concept of the tool having a command as first arguments creates a virtual container for all options and isolates it from the other commands. For instance, the following example shows the problem of dealing with arguments that are not compatiable. Which one is the right command to execute? (create session or create kernel channel).

```
$ lttng --session my_session --kernel --channel chan1
[bad command]
```

1. `http://git-scm.com`
2. `http://gnupg.org`

However, looking at the git alike example, we don't even need to examine the correct versus bad arguments. The command is *create* hence use to create a session so the following options are simply not applicable.

```
$ lttng create my_session --kernel --channel chan1
```

All arguments and options following the first parameter is consider to be applied on the specific command passed to `lttng`. Here is the list of today's commands and you will notice that we went for a semantic of one command is one tracing action.

```
add-context     Add context to event and/or channel
calibrate       Quantify LTTng overhead
create          Create tracing session
destroy         Tear down tracing session
enable-channel  Enable tracing channel
enable-event    Enable tracing event
disable-channel Disable tracing channel
disable-event   Disable tracing event
list            List possible tracing options
set-session     Set current session name
start           Start tracing
stop            Stop tracing
version         Show version information
view            Start trace viewer
```

One possibility was to merge *enable-event* and *enable-channel* under one command being *enable* using event and channel as arguments. However, these two commands have very different options and we endup with the UI one inside a supposedly action container. So, we went for the most specific action we could and made arguments and options handling much more easier.

On the usability side, this is the best way we found to present all available LTTng features to the user. A normal user not knowing anything about tracing can and should understand quickly how to operate it just by looking at the possible actions instead of possible command line options. Of course, we always recommend to RTFM :).

Please refer to the lttng.1 man page for more information (Goulet, 2012).

## Control library

We've mentionned above the control library which is the backbone of `lttng`. Quick note on that and how it is working along side with the session daemon.

Upon startup, the session daemon creates a client Unix socket which shall only be used by the control library. If the session daemon is running with privileged credentials, the write permission is set for the tracing group hence anyone in the tracing group is able to trace the kernel. If it's running under normal credential, this socket is created in the home directory of the user and only him or her can interact with the session daemon.

For each API calls of the control library (Ex: `lttng_enable_event(...)`), a connection is established to the session daemon where the session name, domain and credentials are passed over the socket along with the command and related options. The socket is than closed and the returned value is given to the user.

Also, remote control is planned for mid-2012 and will rely on a secure communication channel using SSH2 protocol (Ylonen *et al.*, 2006). This is the last step for an almost complete tracing integration for data centres. The ability to control tracing over the network is a very demanded feature and is crucial for large scale monitoring. The control library will be extended to support remote control and a possible new command/actions will be added to the `lttng` command line interface.

Final note. In order to control tracers (lttng-ust and lttng-kernel), the LTTng 2.0 toolchain's design imposes that every command has to passed through the session daemon using this control library. There is no other way to do so by design.